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1. S U M M A R Y

The report this month consists of two parts:

1.1 PULSE-JET ANALOG CIRCUITS

Detailed circuit diagrams for all aspects of the Pulse-Jet Analog are presented, together with descriptions of each circuit and the functioning of all components. This description is functional only, i.e. we are merely explaining the operation of the circuit. We are not for this immediate purpose attempting to justify or explain the principles and concepts which are the basis for these circuits. This material is presented prior to the issuance of the final report on the development of the Analog to facilitate the understanding of the work which is continuing.

1.2 STUDY OF COMBUSTION TIME AND VALVE RESISTANCE

The use of the Pulse-Jet Analog as a development tool has been started with a study of two parameters in the system, viz. the combustion time and valve forward resistance. It has become forcefully apparent to those working with the Analog that there are a great many interrelated parameters within this system. In such a highly complex system, it is easy to become confused when one attempts to operate with too many complex parameters in an early stage of the work. Therefore, for our work this month, we have purposely eliminated many complicating factors and used a simplified form of the Analog so that the essential operating factors can be readily distinguished. It should be constantly remembered when studying the data here presented that we are operating with a simplification of the complete system and that many parameters which are presently ignored will undoubtedly have an essential influence upon the type of operation which this preliminary study describes. Nevertheless, certain essential aspects of combustion time and valve impedance are clearly demonstrated.

2. INTRODUCTION

This report describes work accomplished on item 1.7 of Exhibit A, Supplementary Agreement No. 5 of Contract AF33(600)-5860 during the month of September, 1953.

This is the first monthly report to be submitted describing the use of the Pulse-Jet Analog as a design tool for development purposes. The report is submitted by the American Helicopter Co., Inc., describing the study program being conducted by Paul S. Veneklasen, Consultant in Acoustics.

The work was carried out and is reported by Paul S. Veneklasen, and staff members W. B. Snow, G. F. Brockett, M. O. Herwick, and D. E. Talbert.

3. D I S C U S S I O N

3.1 CIRCUIT DIAGRAMS AND FUNCTIONAL DESCRIPTION OF PULSE-JET ANALOG

3.1.1 Block Diagram of Pulse-Jet Analog

Fig. 3.1-1 has been prepared to illustrate the various parts of the Analog and their relation to the Pulse-Jet engine. At the top is a schematic of an engine, while below it is a block diagram of the Analog, with analogous parts indicated by appropriate width or character of line. In the engine fuel is injected and mixed with air admitted by the valves. When the fuel is ignited energy is released in the form of heat in a quantity essentially independent of the ambient conditions. It will be seen that the Analog contains a block simulating the action of the valves, which controls a block simulating the inflow of air. The combustion is simulated by a block labelled "Energy Addition."

In the engine the release of heat causes a pressure to be developed in the tube, and a wave of pressure and high-velocity gas travels down the tube to the open exit end, where gas is expelled. The wave motion in this tube is simulated by the long block shown in the Analog. Operation of the engine is also characterized by reverse flow at the tailpipe following the initial exit of gas, the relation between the effects being controlled by the end flare. An air load reaction block is shown for the Analog.

Following the positive pressure wave in the engine there is a period of negative pressure which opens the valves, and admits fresh air and more fuel. This negative pressure is succeeded by a positive pressure, at which time ignition takes place. Thus in the engine these various phenomena are interdependent and self-sustaining. The arrows between the Analog blocks indicate similar action. The valve action is controlled by the engine tube Analog, but it in turn affects operation by controlling the simulated air flow back into the tube Analog. The energy addition block is controlled in time of operation by the engine tube Analog to maintain the repetitive operation.

At the bottom of the figure is a more detailed block diagram of the Analog, indicating the various functions required to perform these operations. Since this is a closed-loop or oscillating system, an arbitrary choice must be made in selecting a starting point for a description of operation. Assume that the system is running and just entering the phase of negative pressure at the valve end. The engine tube

is simulated by an electrical line, and voltage on the line corresponds to pressure in the tube. A negative voltage at the input to the Line (J201) drives an electronic Valve Mechanical Resonance circuit "open". The Position Detector senses the amount of opening and controls a Valve Opening circuit which allows current flow, simulating airflow, in the Line input through an electrical impedance simulating Airflow Impedance. When the Line voltage is positive the circuit should simulate valve closure, which is done by the feed-back Valve Stop circuit. The Position Detector and Valve Opening circuits cooperate to stop "air-flow" current when the valve simulator indicates closed valves.

In the Energy Addition panel, a small positive increase in Line voltage above zero is sensed by the Ignition Function circuit, which then initiates the generation of an electrical wave form simulating the combustion process in the two boxes shown. This wave form, after adjustment of level in the Fuel Flow simulator, is impressed as a current pulse in the Line by a circuit whose performance is independent of Line voltage. This current pulse generates a high positive Line voltage pulse, analagous to the high combustion pressure pulse in the engine. This pulse now proceeds down the Line, and is reflected by the Line Termination in a manner analagous to the effects at the end of the tube in the engine.

The following sections 3.1.2 to 3.1.5. contain detailed schematics of all circuits in the Analog, with descriptions of circuit operation and detailed discussion of the analogy between circuit functions and physical phenomena in the engine.

3.1.2 Engine Tube Analog - Standard Line

The Engine Tube Analog is a 10 section artificial line as shown by Fig. 3.1-2. Its performance has been described in detail in previous reports, particularly RR12 and RR13. It has a cut-off frequency of 14,000 cps., a fundamental resonant frequency of approximately 1,000 cps., and characteristic impedance of 4420 ohms. For all frequencies below the cut-off, transmission is uniform and with very small attenuation, and the impedance is at Characteristic. The fundamental resonant frequency is dependent on the electrical length of the Line, that is, the number and type of sections, and represents the reciprocal of the time required for a pulse to travel the length of the Line four times.

The Line may be terminated by electrical elements simulating the air reaction load on the engine tube, plugged into J202. R201, plugged into J203, is a current-measuring

resistor, and must be kept small enough to add negligible impedance.

3.1.3 Energy Addition Analog - Panel 400

In the engine, energy is added by combustion of fuel, with the addition of only about 1/15 to the mass of air. This raises the temperature of the gas and creates a positive pressure increment of about one atmosphere which accelerates the gas molecules and expels them from the tail pipe with increased velocity. This addition of energy is relatively independent of the pressure variations in the engine, once it has been inaugurated by a small positive pressure following a period of negative pressure. To be analogous, the analogy must add energy essentially independent of voltage conditions on the line, and the instant of energy addition must be inaugurated by a positive line voltage following the negative voltage period during which the valves are open.

This is accomplished in the energy adder panel. The requirements on this device are severe, when it is realized that it is actually the feedback circuit of an oscillating system, with its input and output connected together. It must trigger a pulse at the exact instant that a small positive voltage appears across its terminals. It must then lock itself into an inactive condition throughout a subsequent very much higher positive-voltage period and a following negative voltage period. It must deliver a pulse subject to the independence criteria described above, and this pulse must be readily controlable in shape and intensity for simulating a wide range of combustion functions in the engine.

The Energy Addition Analog, which is shown Fig.3.1-3, operates functionally in the following manner. V_{401} and its associated circuits produce a signal pulse responsive in the desired way to line voltage. Then V_{402} and V_{403} produce a sharp timing signal which is applied to the energy addition pulse former, L_{402} - C_{402}, by V_{405}. The shape of pulse used at present is approximately 1/2 of a sine wave. If actual data becomes available on the shape of this function from engine experiments, a new pulse shape can be sibstituted at this point. The pulse shape is then faithfully impressed upon current flow into the line by the circuits associated with V_{406}, V_{407} and V_{408}. Once the timing signal has been generated by V_{402} - V_{403}, this sequence proceeds regardless of input voltage conditions, provided the energy addition pulse is shorter than a full cycle of engine operation.

The details of this operation are as follows: The circuit is coupled to the ~~line by~~ cathode follower V_{401} which presents a high imp~~edance to~~ the CLASSIFICATION CHANGED TO imped-ance to diode D_{401}. D_{401} is so pole[redacted]gative

waves and conducts positive waves. Therefore, negative line voltages have no effect on the energy addition. The diode output current is now differentiated by R401 and L401 to limit the triggering sensitivity to rates of voltage increase greater than a selected minimum. An inductive circuit is used, rather than the more common capacitive differentiator, to preserve dc continuity and maintain constant average grid bias on V402. D402 is poled to clip the negative "tails" of the differentiated wave before the signal is applied to V402. Therefore the signal at this point is responsive only to positive line voltage (engine pressure above atmospheric) and is proportional to the amplitude and rate of change of this voltage.

V402 and V403 form a high gain amplifier which is greatly overdriven to produce a square wave output. V402 has its cathode maintained above normal bias potential, extending the linear operating range since the grid drive voltage can go only positive and no negative-following range is required. By adjusting the cathode voltage to an even higher value the tube can be operated in a cut-off position and a threshold type of action in addition to that given by the discriminator can be obtained. Then the input voltage must exceed a certain positive value before any plate current is drawn.

When current flows, the plate voltage follows to positive tube cut-off where the wave is squared off. This voltage is applied, via C401 to D403 and the grid of V403. (500 ohm resistor R402 is to suppress parasitic oscillation only). The grid voltage on V403 has both positive and negative portions because the average current through C401 must be zero. D403 is inserted to aid the grid in absorbing the positive over-drive without blocking, while the very steep transfer to negative cut-off gives the essentially square wave front desired.

This steep front is differentiated by C403 and R403 and applied to the grid of cathode follower V405, which has its cathode voltage maintained at negative cut-off voltage so that it can relay only positive pulses. The positive output pulse causes the tuned circuit L402 - C402 to start to "ring" at its natural frequency, but diode D404 conducts during the negative portion of the first cycle and effectually dissipates the energy. The voltage across C402 therefore consists of a positive pulse of the shape desired for inserting into the line. Note that the capacitor and inductor are plug-in units, facilitating change of pulse length.

The problem now is to transfer this wave form into the line, while very high impedance is maintained. This is done by the amplifier consisting of V406, V407 and V408, in which V407 and V408 are used in [redacted]

current of 8 ma. The amplitude of this current is adjusted by means of potentiometer P_{401}, which is analogous to a fuel flow control in the engine. The cathode of V_{406}, in addition to its self-bias resistor, is also connected through a 100 ohm resistor R_{404} and a 10 uf capacitor C_{404} to ground. This 100 ohm resistor is placed in the ground return lead of the line, and consequently provides a current feedback path so poled as to be degenerative. This effect makes the amplifier attempt to maintain constant current into the line, independent of the line voltage or impedance; the amplifier behaves as if it had more than 600,000 ohms source impedance up to an output of 8 ma. V_{409} is a voltage regulator tube used to stabilize the screen voltage on the final amplifier.

The voltage wave supplied to the grids of the final amplifier tubes consists of flat rest portions and positive-going pulses. What current flow direction this will produce in various parts of the cycle depends upon the relation of cathode rest voltage and ground potential, which is adjustable by P_{402}. How this adjustment is determined is described in the discussion of Sec. 3.2.

In this panel as in the others, refinements have been required to obtain adequate performance. Circuits have been isolated by cathode followers to insure ideal impedance condition. Phase shifts have been minimized, and settings worked out to eliminate false or multiple operation. Thus it is possible to connect output to input with stability, and the circuit will produce one large pulse into the line each time it is "ordered" to by the small positive triggering signal.

3.1.4 Valve Action Analog - Panel 600

This portion of the system is designed to simulate the mechanical action of the valves. It receives a voltage from the line which is analogous to pressure difference between atmosphere and the inside of the combustion chamber, and its output is a voltage which controls the airflow-simulating panel (500). It gives accurate simulation for all dynamic conditions and for steady conditions in the ram-pressure direction. In the interest of reasonable simplicity, duplication of static pressure response in the less-important reverse direction is not provided, but can be added in the future by use of a more complicated "valve stop circuit" than the one which is described below.

The action which must be simulated is considered as follows: The valve vanes have mass and stiffness, and if they were mounted freely and plucked, they would vibrate at a

natural frequency determined by these qualities (about 200 cps. in present engines). Actually, in the engine they are mounted so that adjacent vanes touch or nearly touch at rest. Assume that the valve vanes normally just close in still air. Then if a negative pressure is formed inside the engine at the valve position, the valves open and admit air as long as the negative pressure exists. When the pressure reverses and becomes positive, the valves close, and air flow ceases, except for leaks. Since the valve vanes have velocity at this instant, this closing must dissipate the associated energy, which results in high forces on the valve tips, and oscillations of the vanes which may result in bouncing if sufficient damping is not provided. This energy is eventually absorbed as heat. During the period of positive pressure the vanes are pressed shut and are quiescent. Thus each new negative pressure finds the valves in a non-oscillating condition and the valve response is <u>not</u> that characterizing a freely-oscillating resonant system, but only that part of the <u>initial transient response</u> from first opening to subsequent closure.

Actually, because of the valve mass, valve motions lag the pressure changes depending upon the ratio of engine frequency to valve resonant frequency. The airflow resulting from valve opening also lags because of air mass. Both of these effects can be demonstrated by the Analog.

Real valves can be given a pre-tension which will hold them closed under static conditions, or a position adjustment which will hold them open. They are not perfect and leakage occurs even when they are supposedly closed. If the engine is moving, they will be subjected to a uni-directional ram pressure. How these complicating factors are simulated will be described below.

The electrical simulation of these actions is shown in Fig. 3.1-4. Valve mass is simulated by inductance L_{601}, and valve stiffness by capacitor C_{601}. Current in L_{601} represents velocity of the valve reed; charge stored in the capacitor represents the deflection of the reed. This charge is indicated by the capacitor voltage, which therefore can be used as an indicator of reed tip position. Any resonant frequency of valves can be simulated by varying L or C appropriately.

The voltage applied across the inductor and capacitor in series is analogous to the pressure differential in the engine which causes valve action. Since the capacitor voltage represents reed tip position in response to pressure differentials, and the line voltage represents these pressure differentials, line voltage applied to the L_{601} - C_{601} combination will give capacitor voltages which have the correct

timing to simulate valve position in the engine as a function of operating pressures. The position data is used to control circuits on Panel 500, which simulate air flow.

The concept above omits the all-important feature of real valves that they can swing only open and motion is stopped when they return to zero deflection. In the electrical system this corresponds to opening the L-C circuit whenever the capacitor voltage attempts to go negative, but closing it whenever this voltage is positive. To obtain this very fast switching action, recourse is had to the electronic switch furnished by V_{603}, driven by an appropriate sensing and feed-back circuit.

The specific functions of the various elements of the valve action Analog are as follows: V_{601} and V_{602} comprise a direct-coupled amplifier which

(a) furnishes a high input impedance which can be bridged across the line without affecting its performance;

(b) furnishes a very low output impedance from which to drive the valve-simulating L-C circuit, representing the fact that the inrush of air through the valves does not reduce atmospheric pressure;

(c) inverts the phase so that negative line voltage appears as positive drive voltage. This allows the cathode of V_{603} and transformer T_{601}, to operate at low impedance to ground, which eliminates much stray-capacitance trouble.

The voltage at pin 8 of V_{602} therefore represents the force acting on the valve vanes. This voltage is applied through tubes V_{603} and V_{604}, which are poled in opposite sense. Current can flow through V_{604} in the direction representing valve motion in the <u>opening</u> direction at all times since its grid is connected to cathode; it can flow through V_{603} in the direction representing valve-motion in the <u>closing</u> direction, <u>as long as the grid voltage on pin 5 is near zero.</u> However, if a negative voltage is applied by transformer T_{601}, this tube can be cut off, stopping current flow <u>through the main circuit</u>. This results in high voltages across L_{601} as the stored magnetic field collapses, and high-frequency currents flow in the circuit comprising L_{601}, C_{601} and the various stray capacitances, as well as R_{601}, R_{603}, R_{604}, until the energy is dissipated. This process corresponds to the high vane tip forces developed when the valves close, and the local oscillations which are damped by the various mechanical resistances of the valve system. In the Analog [redacted]ances

are symbolic of the valve damping and can be replaced by accurate values when precise information on valve performance is available. The next paragraph describes how this cut-off voltage is obtained. In the following discussion the term "drive voltage" equals line voltage with 180° phase shift.

Assume the drive voltage is just crossing zero in the opening, or positive, direction: Current flows through V_{604} and L_{601} and charges C_{601} which builds up positive voltage. (R_{605} is inserted to enable measurement of this current, and is considered to add negligible impedance). This is analogous to increasing opening of the valves. When the drive voltage reaches its peak and begins to decline, C_{601} begins to discharge and current flows in tube V_{603}. This is analogous to the instant when the valve reaches maximum open position, and its motion changes to the closing direction. Actually, since L_{601} and C_{601} are reactive, there will be a lag between the time the drive voltage begins to fall and the instant when C_{601} begins to discharge. This will be a function of the ratio between drive frequency and valve natural frequency; the closer these are together, the greater the lag.

When the voltage across C_{601} reaches zero, the equivalent instant is reached when the real valve vanes strike, and cannot close farther. Zero voltage indicates zero vane deflection, and at this instant we wish the grid of tube V_{603} to be driven negative so that the drive voltage cannot carry the C_{601} voltage into a fictitious negative region. This stops current flow in the L. C. circuit, corresponding to the stopping of motion (velocity) of the valve. To accomplish this, we derive a voltage from the C_{601} voltage through diodes D_{601} and D_{602}, which are poled to block current flow when C_{601} is positive, but to pass current as soon as it goes negative. The cathode follower V_{605} is inserted between C_{601} and D_{601} because this must be a <u>sensing</u> circuit only and must not affect the capacitor voltage at this point. It presents a high impedance to C_{601} and a desirably low driving impedance to the diodes. It is adjusted so that the dc voltage on pin 8 of V_{605} is exactly at ground potential. Two diodes are used to obtain a high ratio of negative to positive current.

The current passed through the diodes develops a negative voltage on the grid of V_{606}, a cathode follower again inserted to give a favorable impedance transformation. By means of P_{601}, V_{606} is adjusted to give a slight positive bias (about 1 volt) to the anode of diode D_{603}; consequently, the first part of a negative pulse is conducted and develops a voltage change across R_{606}, but when the voltage exceeds the bias of D_{603} the pulse is squared off. We thus have a square wave with very steep sides which crosses the axis at the

instant the voltage across C_{601} starts negative. Since there are no storage elements in the system except stray capacitances, and all impedances are kept low, it follows that the voltage will reverse and cross the axis in the opposite direction with very little delay whenever the C_{601} voltage starts positive.

The square wave just described constitutes the signal required to operate the grid of V_{603}. It is coupled through gain control P_{602}, cathode follower V_{607}, the "valve action amplifier" on Panel 100, and transformer T_{601}. This amplifier has sufficient gain to put -75 volts on the grid of V_{603} and completely cut the tube off even in the face of the high transient voltage which appears across L_{601} because of the switching action. R_{602} is inserted to limit the grid voltage to reasonable values during the positive periods when V_{603} is conducting.

The action of the circuit is, then, as follows: C_{601} voltage would normally swing more than 50 volts negative. As soon as it gets a few tenths of a volt negative, a large negative grid voltage is developed by the circuit described, and the impedance of V_{603} is enormously increased. Current through the main circuit is essentially stopped, and the C_{601} voltage is essentially stopped from increasing in the negative direction. The word "essentially" is used because this is a feedback system, in which the square wave represents the error voltage which inaugurates the control signal which cuts off the tube. The circuit automatically balances itself at some point determined by the gain around the loop, and in this case sufficient gain is provided so that the C_{602} voltage does not overshoot more than 5%.

In principle, this could be done with dc circuits throughout, but in the interest of reducing the complexity at the present stage of development, ac circuits have been employed in the valve action amplifier and V_{603} grid drive. Therefore the stop circuit operates under dynamic conditions, but does not duplicate the stop action for a steady negative input representing a steady internal positive pressure in the real engine. Notice, however, that all circuits are direct-coupled as far as V_{607}. Consequently, the Analog will duplicate valve position performance for the more realistic condition of greater external steady pressure, such as ram pressure on an engine moving through the air.

The voltage on pin 8 of V_{605} represents the valve opening, and can now be applied to a circuit which simulates airflow into the engine. At present no data is available as to the exact relationship between pressure, opening, and flow

velocity, and a relationship simple to secure electronically is used. Any relationship measured in the engine can be duplicated when the data is available. If necessary, the position voltage could be made to control a functional relationship, and the square wave voltage on pin 8 of V_{607} could be used as a timing signal to switch the function in or out depending on whether the valves are open or closed.

A few comments on electronic features of this system appear important. Since the whole purpose of the circuit is to duplicate the time-position action of the valves, and to control other functions in the Analog with this information, delays in its own circuits are very objectionable. Great care was taken to reduce phase shifts in all parts of the circuit to a minimum. V_{603} and V_{604} are low-mu triodes of very low forward resistance even at unusually low plate voltage, which was necessary so that their impedance would have negligible effect on the current in the L-C circuit. This in turn required high negative grid voltage to cut off V_{603}; yet T_{601} was required to have very low self-inductance to avoid phase shift which is particularly objectionable at this point in the stop circuit. Consequently, it could not have a high step-up ratio, and the valve action amplifier had to have a high voltage output with relatively low impedance.

The present panel assumes that the force on the valves is directly proportional to pressure differential across them, since V_{601} and V_{602} comprise a linear amplifier. When an accurate relationship is measured on a real engine, the true function can be inserted in this amplifier.

It was mentioned above that various valve conditions can be simulated in this panel. A pre-tension would be simulated by adjusting pin 8 of V_{602} to have a negative bias (and adding enough negative bias to V_{603} to hold it cut off during steady conditions). Then it would be necessary for the drive voltage to exceed this bias before V_{604} would start to conduct, simulating reed motion. A position adjustment representing open valves would be simulated by adjusting this point to have a positive bias. Then steady voltage would appear across C_{601}, representing steady opening. The drive voltage would have to be negative to force the C_{601} voltage to the "stop" condition. The effect of ram pressure would be simulated by a dc voltage in series with the input circuit, poled to tend to place a steady positive voltage on C_{601}.

3.1.5 AIR FLOW ANALOG - PANEL 500

The valve action analog (Panel 600) simulates the mechanical action of the valves in response to line voltage, which in turn simulates the pressure differentials across the valves. In the engine these pressure differentials cause air flow which affects the pressure-time curve. The electrical circuits which simulate air flow are shown in Fig. 3.1 - 5. The air flow analog unit of the system is connected across the line input and its impedance as a function of time is controlled by voltages from the valve action analog. The current flow through the valves modifies the voltage appearing across the line, which in turn affects the charge appearing on C602, and thus the impedance of the air flow circuit. In this manner the pressure-valve opening-flow interactions of the engine are simulated by equivalent interactions in the various panels of the complete Analog.

No experimental data is available on the relation of flow to valve opening and pressure. For the air flow analog, therefore, a simple concept is adopted pending measurement of these relationships. Tubes V501 and V502 are connected, in opposite polarity, across the line in series with plug-in inductor L501 and resistor R501. It can be seen that these tubes have their grids driven by transformers T501 and T502, which are fed in parallel through an amplifier (on Panel 100) from pin 8 of V605 (on Panel 600 - Fig. 3.1-4) - the voltage representing valve position. The impedance of these tubes, therefore, is a function of valve position. Sufficient gain is used so that the tubes are cut off when the C602 voltage is in the stopped region. During this period the line voltage cannot cause current flow at the valve end, representing air flow. When the C602 voltage is positive, indicating open valves, the grids of V501 and V502 are positive, and the tubes conduct with a resistance dependent upon instantaneous line and grid voltages. Now line voltage will cause current flow, simulating admission or ejection of air. Grid current is limited to a safe value by R502 and R503. R504 and R505 and R506 are current-measuring resistors considered negligible in circuit functioning.

Current will flow only one way in a vacuum tube, but the line voltage may be either positive or negative when the valves are open because of delayed action due to valve mass. Therefore two tubes poled oppositely are required so that both forward and backward air flow can be simulated. Vacuum tubes used under these conditions do not have simple resistance characteristics, although many complex resistance functions can be achieved with these tubes. They are presently used more as switching circuits with relatively low resistance

during the conducting period, and R501 and L501 are inserted to simulate the mass of the air in the valves, and the flow resistance. When the data on flow impedance becomes available, a more sophisticated circuit can be substituted. It will be seen that if the separated system mentioned in the description of the valve mechanical unit must be used, valve position voltage will be used to control the form of the impedance function in a device substituted for L501 and R501, while the stop circuit square wave will control the switching time through V501 and V502. It is to be hoped that the complete simulation can be accomplished through a single device driven by the valve position voltage.

Leakage of the valves is simulated by shunting appropriate impedance elements across the plate-cathode circuit at terminals J503.

3.2 <u>Preliminary Study of Influence of Combustion Time and Valve Forward Resistance on Specific Thrust.</u>

Theoretical studies have repeatedly pointed out that great improvement in Pulse-Jet performance may be expected if the time interval during which energy is released by the combustion process can be reduced to a smaller fraction of the cycle time, i.e. period of the oscillation. With due recognition of the limitations inherent in the electrical analog, it is expected that the Analog should represent a reliable indication of the improvement which is to be attained in this manner.

Another important factor which has not been pointed out in the literature but which has been evident to those engaged in the development of the Analog is the impedance to air flow represented by the valves when they are open and when they are closed. The importance of this factor can only be appreciated when one deals with electrical and acoustical lines and observes the effect on wave motion of the impedances which terminate the extremities of the line. In particular, the essential acoustical resonance of the Pulse-Jet tube is most simply explained on the basis of a tube which is open at the tail pipe end and closed at the valve end. It is duly recognized that the valves are closed during part of the cycle and open during part of the cycle. However, there are many degrees of openness, and the degree to which the valve end is open during the air intake period is what we are describing as valve forward impedance. There is good evidence from measurements on operating engines and the correlation [illegible] this data with the resonant behavior of electrical and acoustical lines that, even when the valves are open to [illegible] air, their impedance to flow is sufficiently high that [illegible] tube still acts essentially as if it were closed.

Using the electrical Analog of the Pul[illegible]-Jet it is possible to adjust these parameters ver[illegible] note the effect on wave motion and on the va[illegible] which indicate performance. Changes can [illegible] the Analog which may be either extremely [illegible] sently impossible in an actual engine [illegible] which may at present seem academic, [illegible] practically attainable at the mome[illegible] indicate the course of worthwhil[illegible] perhaps eliminate costly development [illegible] but less fruitful directions. [illegible] are herein described, the Pulse-Jet [illegible] atly simplified as shown in the block d[illegible] Referring to the detailed diagrams [illegible] the following simplifications have [illegible]

1. The Energy Addition Analog has been used in its complete form.

2. The Tube Analog is used in its simplest form, viz. the standard line. This means that the electrical line simulates a Pulse-Jet tube having uniform cross section area along its entire length.

3. The Tail Pipe Analog is of the simplest sort, viz. a short circuit. This condition represents a completely open end of the Pulse-Jet tube, through which both the outflow and inflow of gases is very readily accomplished.

4. The Valve Analog is extremely simplified, being represented by a simple diode with a series resistance. This simplification is analogous to valves which are massless and extremely flexible so that they open completely and instantaneously when a negative pressure is applied. The resistance limits the rate at which air can be drawn into the combustion chamber when the valves are open. The diode and resistance therefore represent the simplest form for both the valve mechanical and air flow analogs.

The approach which is taken for the following tests is therefore to use an extremely simple form of the analog, varying just two parameters, viz. the pulse length in the Combustion Analog and the series resistance in the Valve Analog. We believe that it is better to make our initial investigation with a simple analog rather than to use a complex form of the analog with certain arbitrary settings of the many complicating parameters. It will be very evident in the data which follows that the latter course even in this preliminary test would have hidden a very important conclusion, because if one chooses an arbitrary adjustment for a certain parameter, without foreknowledge of the implications of such an arbitrary choice, he may have chosen exactly the adjustment which will obscure the major factor which is under study. It is greatly preferable to eliminate temporarily such complicating factors, find the optimum setting for a few remaining parameters, and then add the

other parameters one at a time, noting the effect on the performance with the optimum setting.

The data which results from a study of the combustion time and valve forward resistance is here presented in three different forms, i.e. the graph of Fig. 3.2-2, the Table 3.2-3, and the photographs Figures 3.2-4 through 3.2-11.

The significance of the data is most readily described in relation to the photographs of the oscillographic data, for which we choose Fig. 3.2-7. Four oscillographic traces show the essential behavior of the system. The upper trace shows the current delivered to the system by the Energy Addition Analog and is labeled Source Current. The space interval between the two pulses represents the time for one cycle of the engine. All the other oscillographic traces are aligned vertically with respect to the upper trace so that the timing or phasing of all other events is properly indicated with respect to the Source Current. As a general statement, ignoring much discussion of concept, we may say for the present purpose that the electrical Source Current delivered by the Energy Addition Analog to the electrical line represents the <u>Rate of Combustion</u> or, more properly, the rate of energy released by combustion. In the particular figure which is chosen for the present discussion, the combustion interval is quite short, i.e. the order of one-tenth of the cycle period, which is by no means similar to that achieved in present Pulse-Jet engines. Other figures, such as Fig. 3.2-4 show combustion times which are more similar to present operating conditions. The short combustion time is chosen for this discussion because the resulting wave motion within the system is more readily apparent.

The second oscillographic trace shows the voltage which appears at the input end of the electrical line where the Source Current is introduced. It should be noted first that the <u>Line Input Voltage</u> can have an entirely different form from the Source Current. This essential feature is inherent in the nature of the Energy Addition Analog, i.e. it will feed current into the line in a manner which is independent of the resulting behavior of the line itself. In other words, the Energy Addition Analog is a very high impedance source of current. This statement expressed in terms of Thevenin's Theorem says that the current generator can be represented by a voltage having the wave form of the current pulse in series with a very high resistance. This high resistance in series with the generator permits the line voltage to vary in a manner which is determined by

the line parameters rather than the source parameters. The Line Input Voltage is analogous to the Chamber Pressure which is generated in the combustion chamber just inside the valves. It will be noted that in between the positive pressure pulses caused by successive current pulses a negative pressure pulse appears. This negative pulse is the reflection of the positive pulse which has traveled down the electrical line to the short circuit end and has been reflected with a reversal of phase, just as in an acoustical tube a positive pressure wave travels down the tube and is reflected at the open end in such a manner that it returns as a negative pressure pulse. It should be noted that this negative voltage pulse or pressure pulse occurs exactly one-half a period after the pulse of source current. Many fine points appear in the traces which are purposely not discussed herein to confuse the major issues.

The third trace indicates the current flow through the valves. The Valve Input Current, which is analogous to Air Intake Flow, flows as a result of the voltage drop which appears across the valves, i.e. between Electrical Ground, which is analogous to Atmospheric Pressure, and the Line Input Voltage, which is analogous to Chamber Pressure. Therefore, when the Line Input Voltage goes negative, the Valve Input Current commences to flow. It should be remembered that this will occur strictly only in the simple case which is here presented. Valves which have mass and which entrain a mass of air do not permit such instantaneous reaction between chamber pressure and air flow. The large negative portions of this third trace represent current flow from ground into the line through the diode, which is a low resistance by virtue of the negative voltage across it, and through the series resistance, which is 7,000 ohms in this case. It should be noted that during the pulse of source current when the line input voltage is high, there appears a small positive pulse in the Valve Input Current trace. This positive pulse represents current flow in a reverse direction, i.e. out of the line into ground, which is analogous to reverse leakage of gases through the valve. This is intended to be a negligible feature of the simple analog used in these tests but is evidence that the diode possesses a high but not infinite resistance when there is a positive voltage across it.

The fourth trace represents the current flow at the output end of the electrical line which is short circuited. This current is measured by the voltage drop across a 30-ohm

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resistance which, while not quite a short circuit, has been shown to have negligible effect upon the circuit. The positive pulse represents a flow of <u>Line Output Current</u> from the line into electrical ground, which is analogous to the <u>Exhaust Gas Flow</u> out of the tail pipe into the atmosphere. (Many possibly confusing aspects of the analogy between electrical ground and the atmosphere surrounding an operating Pulse-Jet engine are discussed in the detailed report on the Analog development.) A negative pulse of Line Output Current is analogous to the re-entrant flow of air back into the tail pipe, which is known to occur in operating engines. It will be noted that the positive current pulse occurs exactly one-quarter period after the pulse of source current. This current flows in response to the positive voltage pulse which occurs at the input end of the line and travels down the line to the short circuited end in one-quarter of the cycle time. The negative current pulse results after this same wave has traveled back along the line to the input end and has again been reflected as a negative voltage wave from the valve end and travels down the line to draw current inward at the short-circuited end. This is analogous to the travel of the positive pressure wave down the acoustical tube which causes the outflow of gas at the tail pipe, resulting in the return of a negative pressure wave to the valve end of the tube, where it is reflected as a negative pressure wave, which travels again down the tube and draws air back into the tube.

(It is important to become accustomed to the concept of waves traveling in acoustic tubes and in electrical lines. Much literature has falsely conveyed the concept of such waves appearing always as pressure variations, which is not the case. A wave pulse traveling in a tube has at least two types of manifestation: In regions where the wave is encompassed by walls it exhibits pressure. At or near the open end of a tube, where the wave is not thoroughly emcompassed but is exposed to the atmosphere, pressure cannot be fully developed and the wave takes the form of movement of the medium, i.e. flow of gas current. The generation of positive or negative pressure is reproduced in the Analog as electrical voltage, while the movement of the medium is represented by the flow of electrical current. At any given point in the system either or both of these aspects of wave motion may appear in varying degrees depending upon the acoustical or electrical impedance at that point. At a point of low accustical or low electrical impedance the current flow will be most evident. Thus, the travel of a wave in a tube will represent a continual interchange between pressure energy, i.e. potential energy, and current flow, i.e. kinetic energy.)

Thus the four oscillographic traces represent the essential features of the voltage and current behavior in this simple form of the Pulse-Jet Analog as a response to the current injected into the system at the valve end of the electrical line, which is analogous to the response of the Pulse-Jet engine to the release of heat energy and the resulting behavior in terms of pressure and gas flow.

In the following series of traces we show the effects on the behavior of the system which result from variations in two parameters, viz. the time interval during which source current flows and the value of the resistance which is in series with the simple diode valve.

The results of this initial study are presented in their entirety in the graph of Fig. 3.2-2. All data for this graph is tabulated in Table 3.2-3. Representative points from the graph are chosen for a photographic presentation in Figs. 3.2-4 through 3.2-11. The photographic series fall into two groups: those having short pulses of source current, and those having long pulses.

All points on this graph share certain conditions in common:

1. The electrical line is the simple uniform line of Fig. 3.1-2, which represents a Pulse-Jet tube having uniform cross section along its length.

2. The termination at the output end of the line is a short circuit.

3. The system is a driven system. The re-ignition, i.e. the repetition of the electrical pulse, is not initiated by reflections from the electrical line. The system is driven externally from an electrical oscillator. The driving frequency is 1,000 cps., which is identical with the fundamental resonant frequency at which the Analog would normally operate as a self-driven system under the appropriate conditions of termination. The reason that the system is driven externally, rather than used in the self-excited condition~~, is that~~ mahy of the termination

conditions which are used in this study would not permit self-excited operation or would at best result in a self-excited frequency which would vary over wide limits. It waw not desirable that this additional variable should be injected into the study.

4. The following adjustment in source current was always made: The Energy Addition Analog is first adjusted so that <u>during the quiescent period</u> the source current as observed on the oscilloscope is exactly zero. Under this adjustment the averaging meter which measures the source current reads the Total Current delivered by the Energy Addition Analog. The zero balance is then shifted so that the Average Current as read on the meter is zero. This means that the current during the quiescent period will no longer be zero but rather will be some negative value such that the total current delivered during this negative interval equals the total current delivered during the shorter positive interval of the pulse. It will be evident from the oscillographic traces that the peak value during the pulse is therefore much greater than the steady value of negative current delivered during the quiescent period.

The reason for this adjustment is as follows: In the actual Pulse-Jet engine the combustion process does not contribute significantly to the total mass flow in the system since the fuel/air mass ratio is small. In other words, the total mass flow from the tail pipe is approximately equal to the total mass flow through the valves. Correspondingly, in the Analog the total current in the output termination should equal the total current through the valves. Tests have been made to show that, if the source current is so adjusted that it is zero during the quiescent period, the same results may be obtained by subtracting the average source current from the output current.

A great deal must be said to justify attributing the term "thrust" to any measurement derived from the Analog. Recognizing that such explanation is [redacted]inal

Report on the development of the Analog, we limit ourselves here to explanation for our immediate purpose. Under the specific circumstances represented by the present tests, the thrust may be derived from the Line Input Voltage and is proportional to the average voltage appearing across the input of the line.

Fuel Flow is proportional to the Total Source Current. Therefore, we take, as a measure of the effectiveness of a given adjustment of the Analog, the ratio of average Line Input Voltage to the Total Source Current and call this ratio the Specific Thrust.

An important quantity in the behavior of an electrical line and of an acoustical tube is the Characteristic Impedance of the line. When the electrical line is terminated in this Characteristic Impedance, no reflections can occur at the termination. In other words, energy which travels along the line is completely absorbed when it reaches this termination. In the case of our electrical line, the value of the Characteristic Impedance is a pure resistance of 4420 ohms. If a line is terminated in an impedance greater than this value, the reflections from the termination will be in phase with the approaching wave. If the termination is less than the Characteristic value, the reflected waves will be reversed in phase.

The graph of Fig. 3.2-2 then tells the following story:

1. Pulse-Jet engines, as presently used, are most closely simulated by the data on the long pulse with valve resistance somewhat greater than the characteristic resistance. Such a condition is represented in the graph of Fig. 3.2-4. In this case the Line Output Current shows both positive and negative phases.

2. As the valve impedance is decreased, the Specific Thrust gradually increases along with the Valve Input Current and the Line Output Current. The behavior of the system as the valve impedance is decreased and the reasons for the increase in Specific Thrust are shown in the series of Figs. 3.2-4, 3.2-5 and 3.2-6. It will be noted that the Source Current curves are identical for this series. The Valve Input Current steadily

increases. (To properly appreciate the relative magnitudes of the curves, the sensitivity setting of the oscilloscope should be observed. It is realized that in the future more appropriate settings may be used to facilitate comparisons between the curves of a given series. Also photographic techniques are evolving.) The reasons for these increases are as follows: In the case of Valve Input Current, the flow is essentially in one direction in all cases so that the increase in average current is evident by an increase in area under the trace. (Note the factor of 2 in scope sensitivity in Fig. 3.2-6. In the case of Line Output Current, not only the area under the curve is increased but the proportion of positive to negative current increases. For a high value of valve forward resistance, as in Fig. 3.2-4, there is considerable reverse current flow at the line output corresponding to re-entrant air in the tail pipe of an operating engine. As the valve forward resistance decreases, the amount of this reverse current decreases, and it disappears in Fig. 3.2-6, where, in fact, instead of a reverse flow we have a second positive flow during that same interval of time. In other words, for a low valve impedance we have two exhaust pulses per cycle.

3. The series represented by Figs. 3.2-7, 3.2-8, 3.2-9 and 3.2-10 are characterized by a much shorter interval of source current, viz. about 1/10 of the cycle instead of 6/10 of the cycle. If the valve forward resistance is high, the Specific Thrust is about the same as for the longer pulse. In other words, <u>shortening the combustion pulse does not of itself produce an increase in Specific Thrust if the valve impedance is greater than Characteristic Impedance</u>, which is quite evidently the case for present types of Pulse-Jet engines. However, as the valve impedance is decreased, the Specific Thrust increases more rapidly with the short pulse. In fact, an improvement by a factor of more than four is shown within the range of the present data.

4. The reason for this increase is again made clear by a comparison of the series of figures. In the case of a high valve impedance, the flow of Valve Input Current occurs over a rather short time interval. The line output current shows both a positive and a negative phase corresponding to inflow as well as outflow of exhaust gas. When the valve resistance equals the characteristic resistance, the reverse flow has all but disappeared and the magnitude of the positive pulse has substantially increased. As the valve resistance is further decreased, the Line Output Current increases rapidly. Instead of the interval of reverse flow, two exhaust pulses appear and the length of these pulses increases. Note also that the Valve Input Current changes markedly with low valve resistance. In fact, there are two intervals of valve inflow as well as line outflow. Note also a substantial change in the form of the Line Input Voltage, i.e. Chamber Pressure. For low values of valve resistance, the amount of negative pressure is greatly decreased. It will be realized that positive thrust can occur only during intervals of positive chamber pressure and that intervals of negative pressure represent reversed thrust. When the valve resistance is large, considerable negative pressure can be developed; but if the valve resistance is low, a large negative pressure cannot be developed and a greatly increased inflow results from the pressure which is developed.

5. The doubling of exhaust pulses and intake pulses is explained as follows: In the normal Pulse-Jet engine, where the valve impedance is greater than characteristic, the wave motion occurs as follows: The positive pressure wave, caused by the explosion, travels down the tube and appears at the tail pipe as an outflow of gas at the open end and this outflow causes a negative pressure wave to return along the tube toward the valves. When it reaches the valve end, it causes the valves

to open and air intake occurs. However, if the valve impedance is greater than characteristic, this negative pressure wave will be reflected as a negative pressure, and this wave travels down the tube to cause an influx of gas at the open tail pipe end. This influx of gas causes a positive pressure wave to return toward the valve end, where, incidentally, it assists in re-ignition.

If the valve impedance is lower than characteristic, a considerable change in this wave pattern occurs. The explosion causes a positive pressure wave to travel down the tube and results in the expulsion of gas at the open tail pipe. This again causes a negative wave to travel back along the tube toward the valve end, where the valves are opened and an inflow of air occurs. But, if the valve impedance is low, this negative wave is reflected as a positive wave which travels back down the tube and causes a second exhaust of gas at the open end. Thereupon a second negative pressure wave will return toward the valve end, where the valves may again be opened and a second inflow of air may occur. Note, however, that the positive pressure wave which normally assists in re-ignition is lacking in this case; hence, re-ignition would require some other means, such as the injection of fuel against an extremely hot surface.

The important point to be observed from the graph of Fig. 3.2-2 is that the present preliminary study indicates clearly that a decrease in combustion time alone does not offer promise of a significant increase in specific thrust. Since the theoretical studies have not been specific regarding the nature of the valve impedance, it should not be said that this conclusion contradicts those studies. However, the present evidence indicates that for a significant increase in specific thrust it is essential that a decrease in combustion time be accompanied by a greatly reduced valve impedance. These conclusions will undoubtedly be tempered by extension of these studies to include the more complex aspects of the Analog. But it is believed that the fundamentals will be valid.

We wish to call attention, with specific data for evidence, to a possible type of Pulse-Jet operation which has been discovered entirely by use of the Analog and which has provided a value of Specific Thrust which is higher than that given by any of the previously shown configurations. The type of operation upon which this engine configuration is based was suggested by the observed behavior of the electrical line under a certain condition of termination, viz. with a very low impedance output termination representative of an open tube and with an input termination representing valves of low forward resistance. Photographs of oscilloscope traces illustrating this type of behavior are given in Fig. 3.2-11, together with the pertinent data describing the parameters of the system.

The configuration is, in a sense, similar to the multicycle internal combustion engine, in that the frequency of the combustion pulses is considerably lower than the natural frequency of the system. For the particular adjustment shown in Fig. 3.2-11, the electrical line has the usual natural frequency of 1,000 cps. but the system is driven at a frequency of 260 cps. The line output termination is a short circuit, as in previous data, and the valve forward resistance is 650 ohms. The pulse length is .44 milliseconds.

The traces demonstrate the following behavior: As a result of the pulse of Source Current, there is a single pulse of positive Line Input Voltage (chamber pressure) followed by a succession of negative pulses of much smaller magnitude. Valve Input Current consists of a series of inflow pulses, while Line Output Current consists of a series of outflow pulses. In other words, for a single combustion pulse we achieve a series of exhaust pulses and a series of intake pulses. The resulting Specific Thrust is higher than for any of the single cycle configurations.

We do not propose to burden the present disclosure with an attempt at detailed explanations because the behavior and the significance of this system are not at present without obscurity. For example, although the valve impedance is low and therefore the negative Line Input Voltage is proportionately small, nevertheless the interval of such negative voltage is long and, as we have pointed out earlier, this negative voltage or chamber pressure represents a negative thrust. On the other hand, during this same period that the chamber pressure is negative, the traces of current flow indicate clearly that there is a large momentum transfer in the proper direction for positive thrust. For the present we call attention to this behavior and propose to submit the

system to further study and discussion.

We should, however, point out some aspects of this operation, which should be important in actual engine operation, although there is no way for the present form of the Analog to indicate this importance: The Analog is capable of simulating only a cold flow system, whereas in an actual engine large changes in gas density occur. One of the greatest limitations of the Pulse-Jet engine is perhaps the fact that the gas which is being accelerated by each combustion pulse is hot burned gas of low density. However, the type of operation illustrated in Fig. 3.2-11 appears to furnish a mechanism for rather complete scavenging of burned gases, because of the multiplicity of exhaust and intake pulses. If each explosion can operate against cool, high density gas, a considerable improvement should result, in that a larger mass of gas will be ejected at lower velocity, and higher peak pressure will be achieved, and thus more nearly constant volume burning.

Another major advantage should be that the average operating temperature of the engine should be greatly reduced.

It should be pointed out that the type of operation indicated in Fig. 3.2-11 is strongly dependent upon the resonant properties of the Pulse-Jet tube. Depending upon the frictional dissipation within the tube and upon the valve forward resistance, the train of waves initiated by the combustion pulse will be more or less strongly damped. The three lower traces of Fig. 3.2-11 illustrate this damped wave motion. The extent to which the damping is controlled by line resistance or by valve resistance can easily be determined and controlled in the Analog, but we do not have the slightest experimental evidence as to the degree of damping inherent in the Pulse-Jet tube. Nor do we know the nature of the impedance represented by even the present Pulse-Jet valves, except for the low level acoustical tests which give values which are clearly much too low. Again we wish to call attention to the repeated concern for this essential data. The extent to which damping is inherent in the Pulse-Jet tube itself could be determined experimentally by relatively simple means. The valve should be replaced with a rigid plate. The oscillation may be excited with a pressure pulse of realistic value by the use of a firecracker, for instance. If the resulting pressure history is recorded, we will have the damped wave form from which the damping constants of the tube can be calculated.

We wish to urge strongly that such experiments be conducted, not only in relation to the above disclosed type of operation, but also because the use of the Analog has clearly indicated that this damping f [redacted] the most important parameters of the [redacted]

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4. CONCLUSIONS

A. Detailed circuit diagrams for the Pulse-Jet Analog are presented together with descriptions of the operation of each portion of the Analog.

B. A preliminary study has been conducted on the influence of Combustion Time and Valve Forward Resistance on Specific Thrust. A simplified form of the Analog has been used so as to reduce the number of complicating parameters at this stage of the work.

C. Preliminary results indicate that reduction of combustion time alone does not produce significant increase in specific thrust. However, if combined with a reduction in valve forward resistance, very great increases in performance result.

D. Further increase in performance appears possible if the engine is permitted to resonate a few cycles in between combustion pulses. Many additional advantages appear possible with this type of operation; however, auxiliary means for producing ignition would be required.

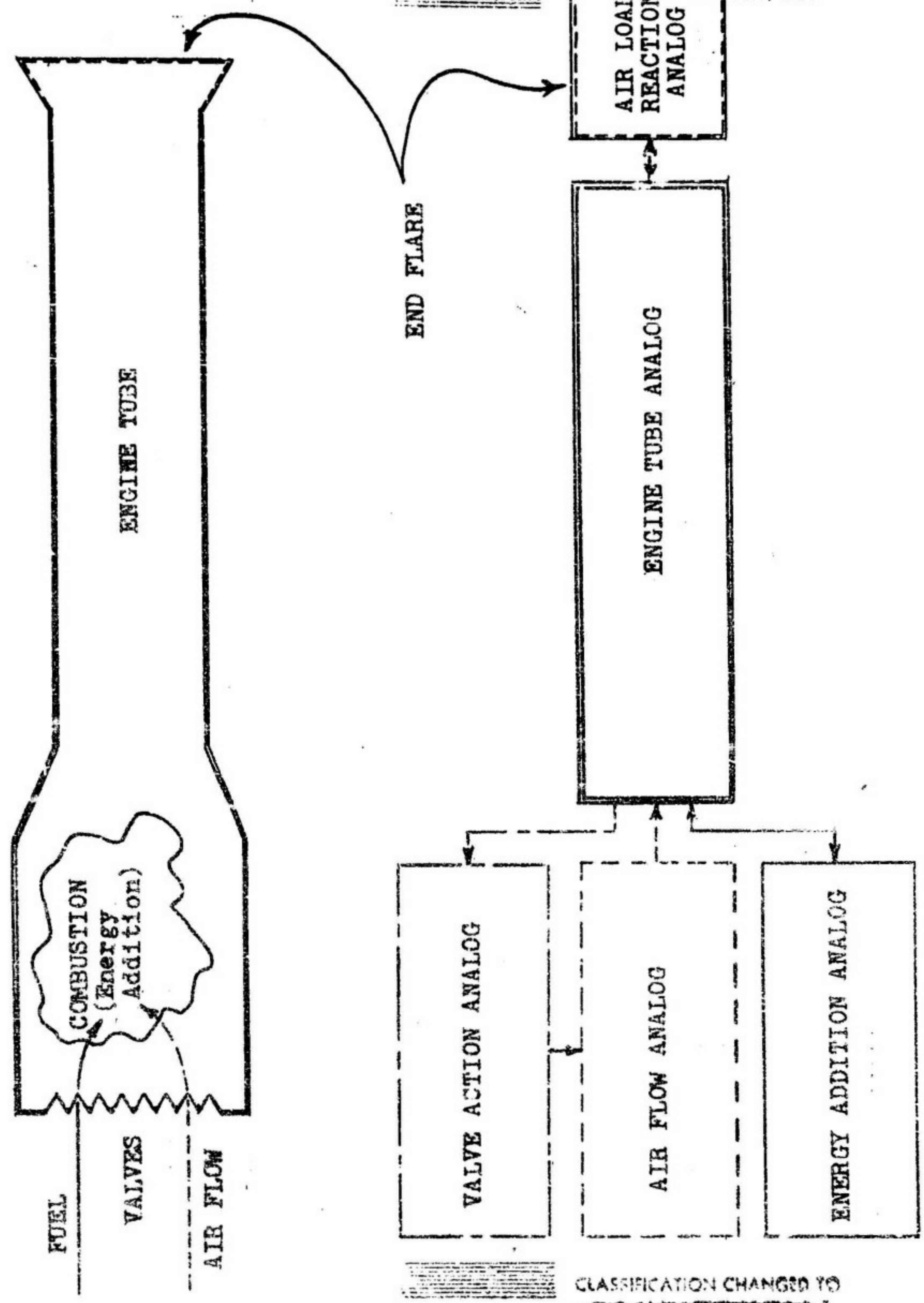
AIR LOAD REACTION ANALOG
END FLARE
ENGINE TUBE
ENGINE TUBE ANALOG
COMBUSTION (Energy Addition)
FUEL
VALVES
AIR FLOW
VALVE ACTION ANALOG
AIR FLOW ANALOG
ENERGY ADDITION ANALOG

FIG. 3.1-1A

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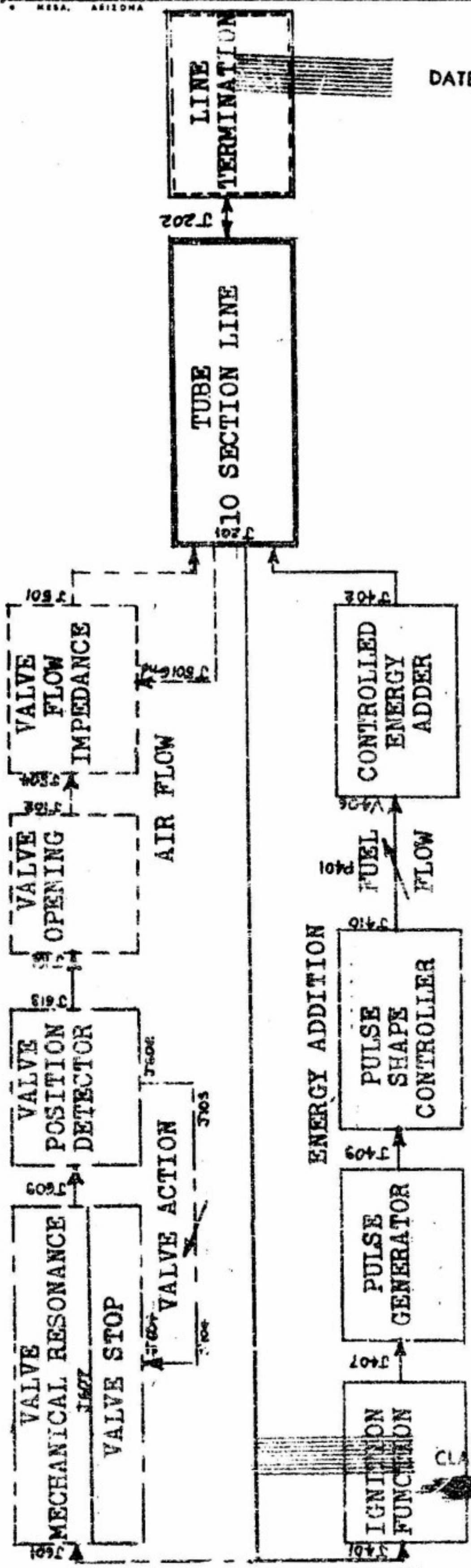

FIG. 3.1-1B

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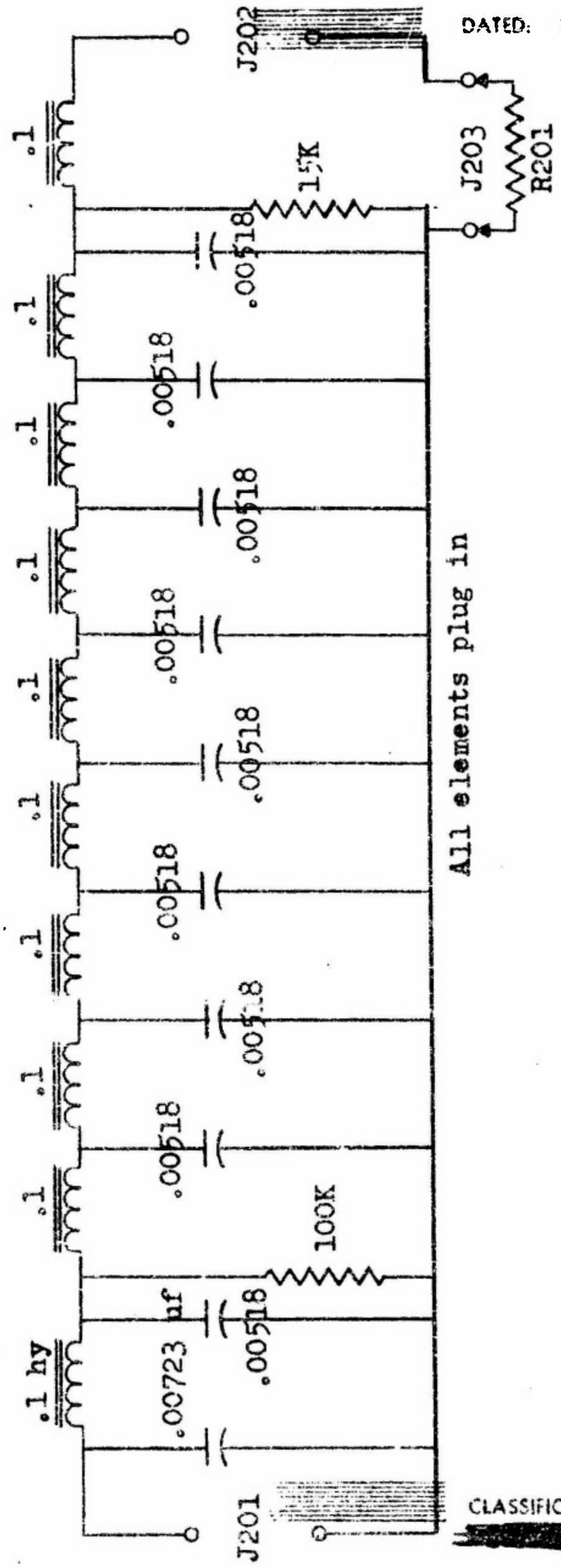

TUBE ANALOG - STANDARD LINE

FIG. 3.1 - 2

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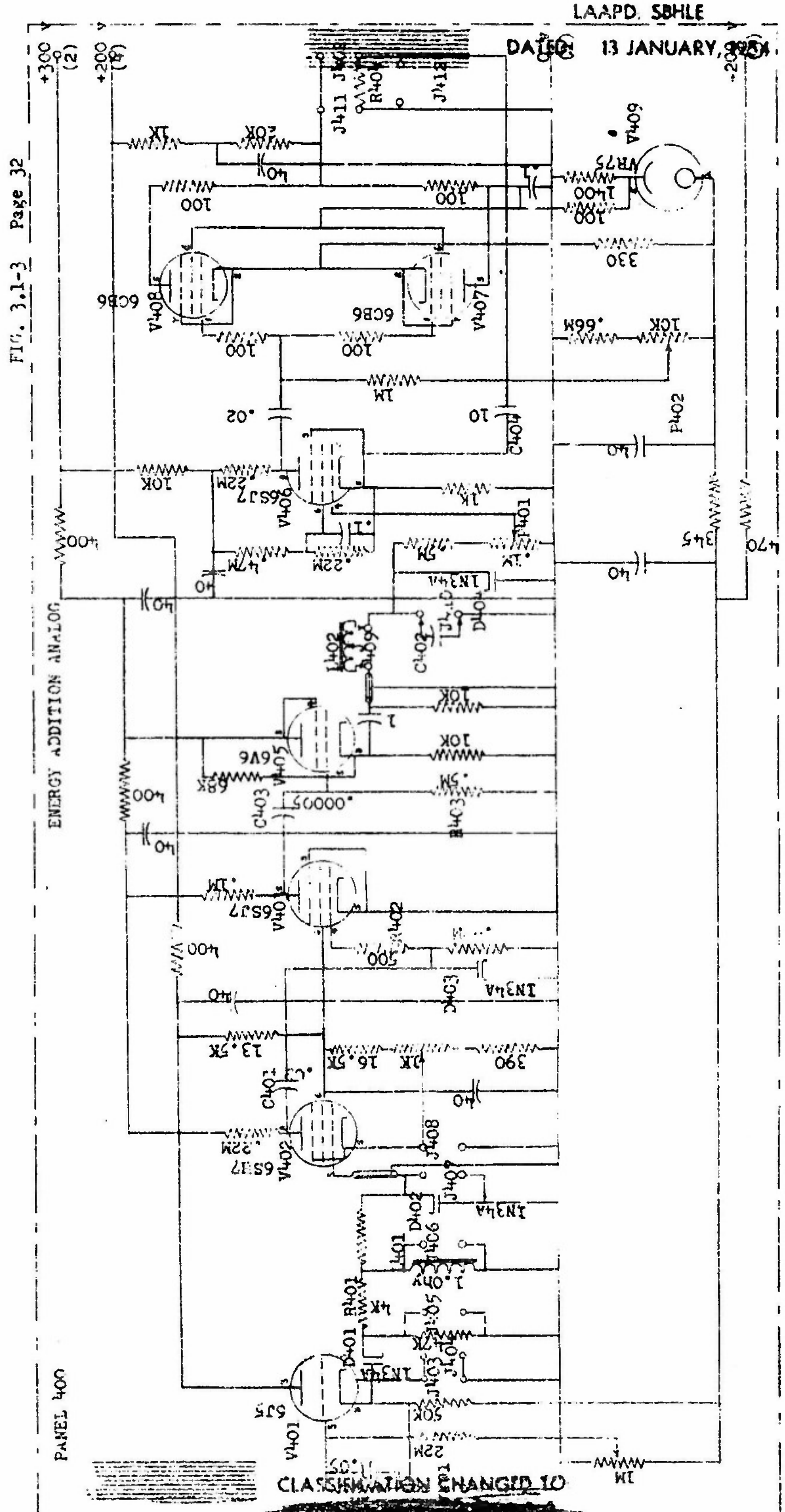

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FIGURE 3.1-3

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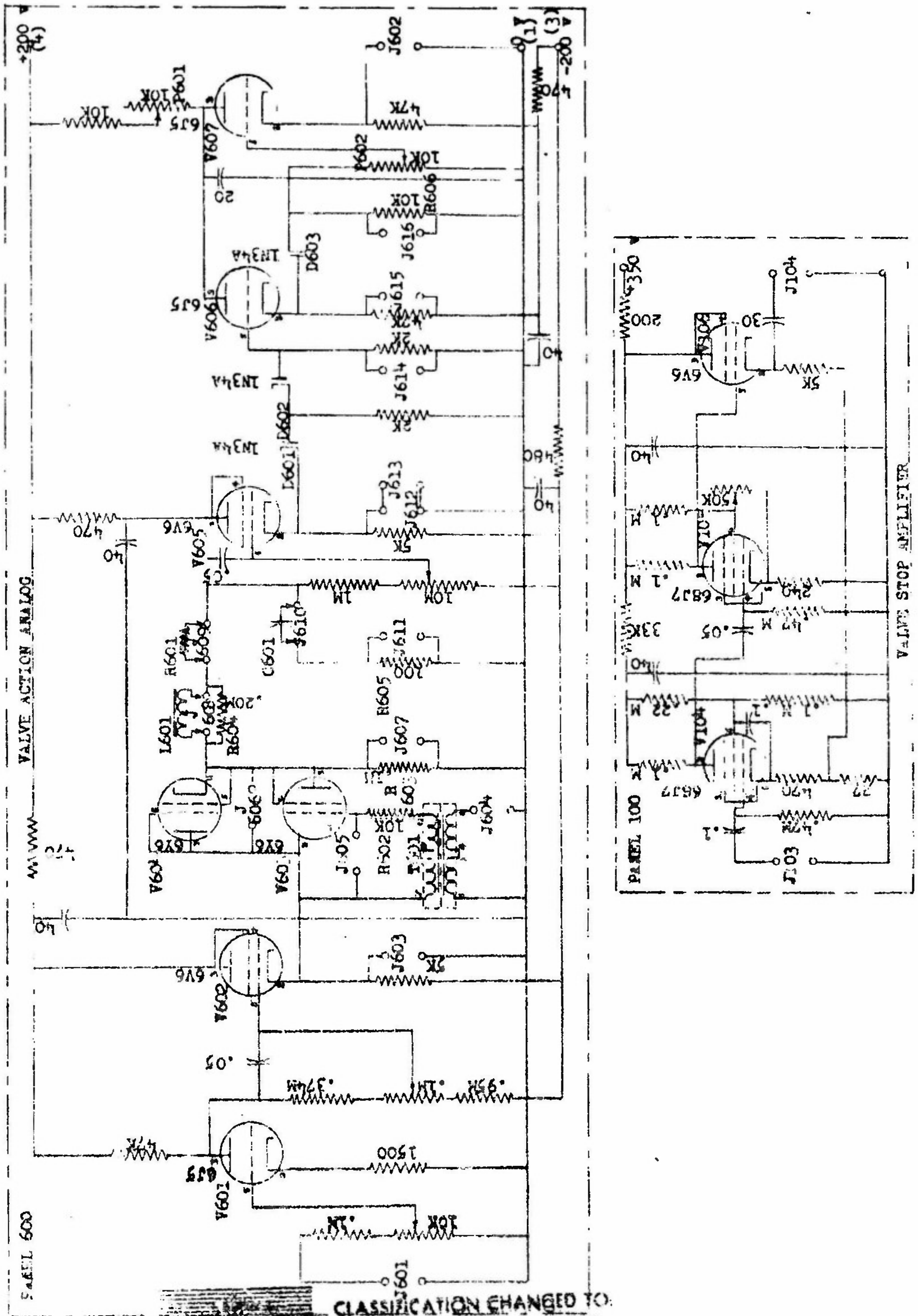

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FIGURE 3.1-4

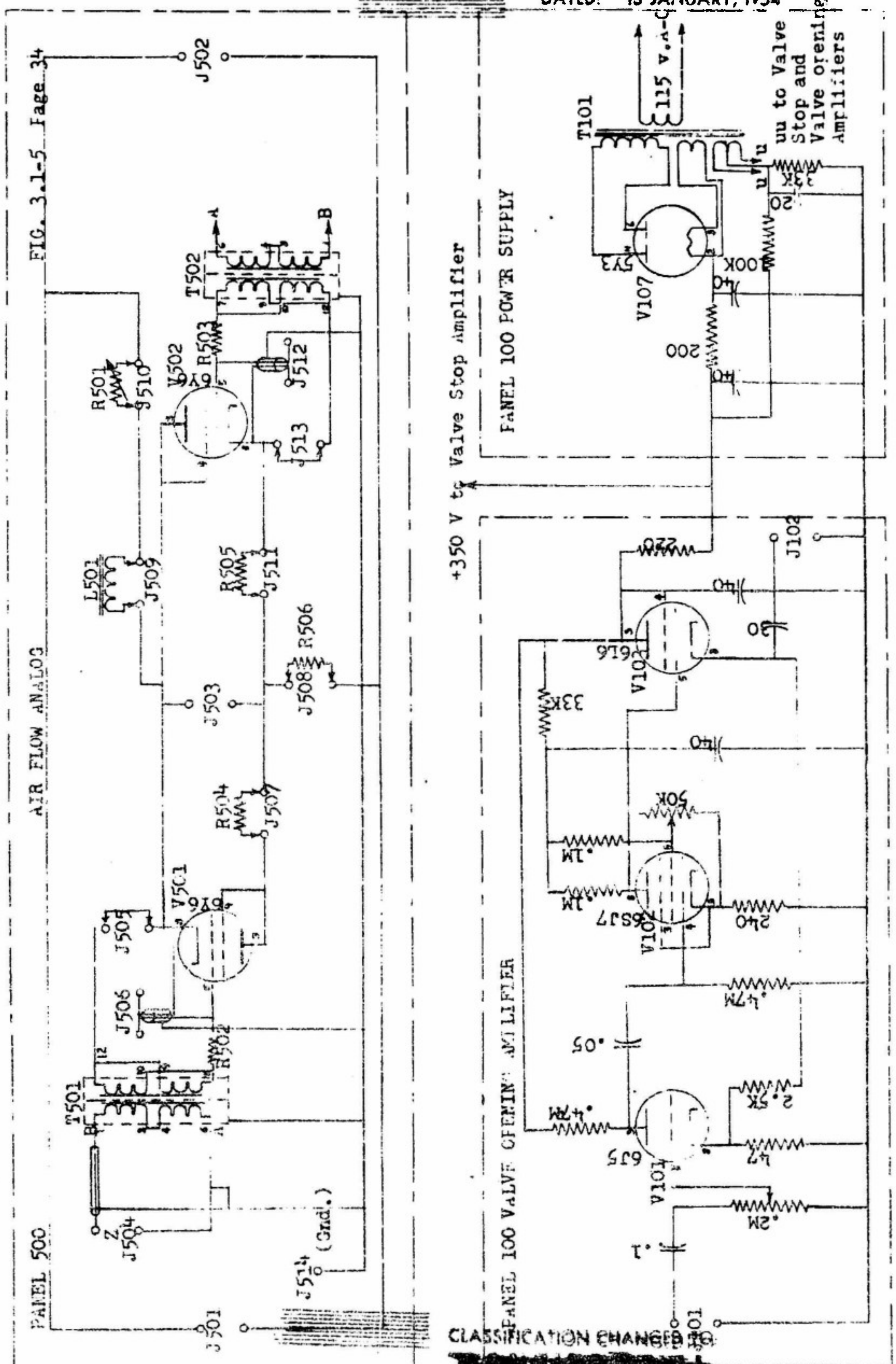
FIG. 3.1-5 Page 34
AIR FLOW ANALOG
PANEL 500
J501
J502
J503
J514 (Grd.)
T501
T502
V501
V502
+350 V to Valve Stop Amplifier
PANEL 100 POWER SUPPLY
T101
115 v.a-c
V107
5Y3
V102
6L6
V101
6J5
J101
J102

FIGURE 3.1-5

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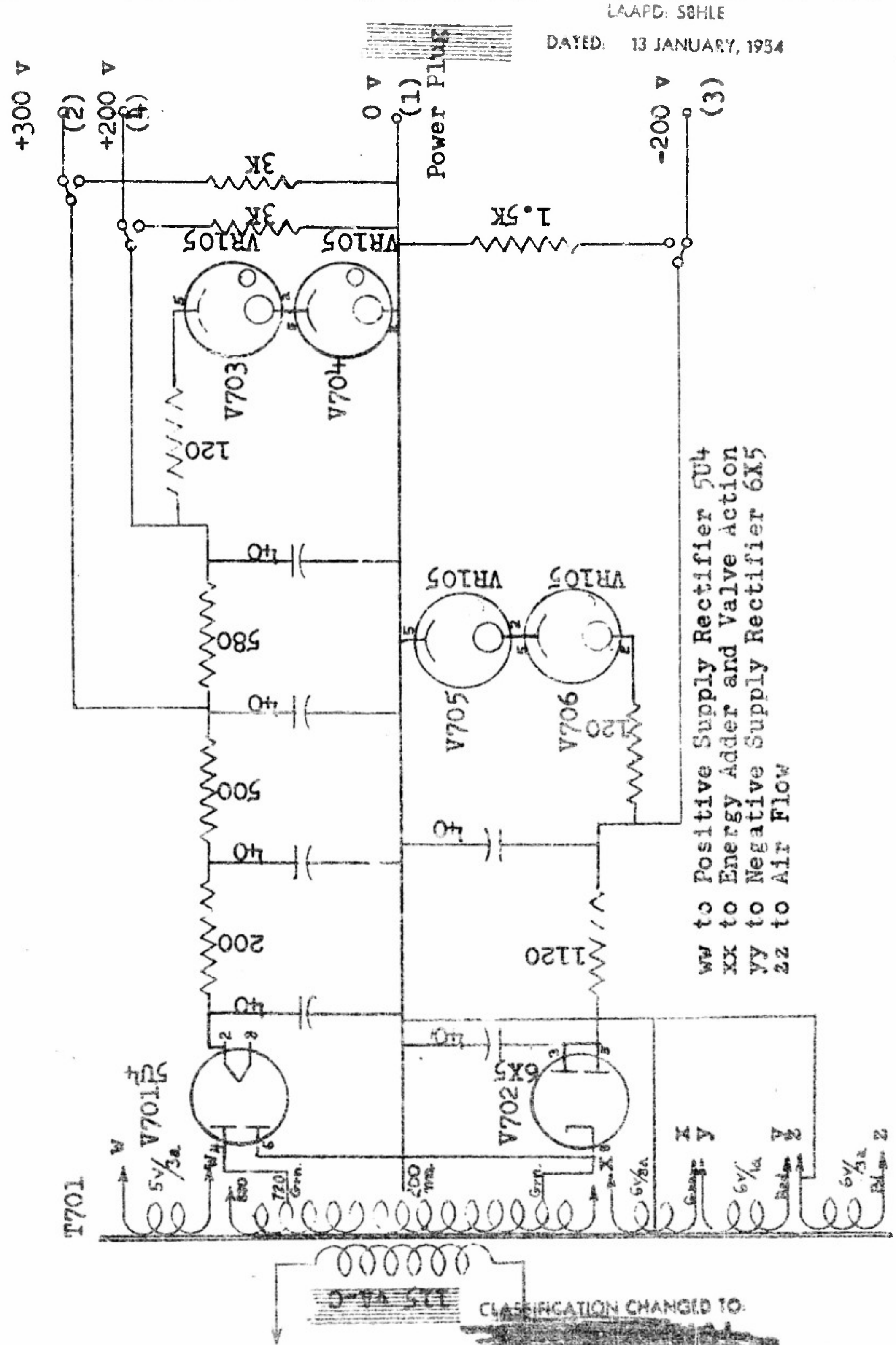
FIG. 3.1-6 Page 35

POWER SUPPLY



PANEL 700

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SIMPLIFIED ANALOG USEDIN PRELIMINARY STUDY OF COMBUSTION TIME AND VALVE RESISTANCE.

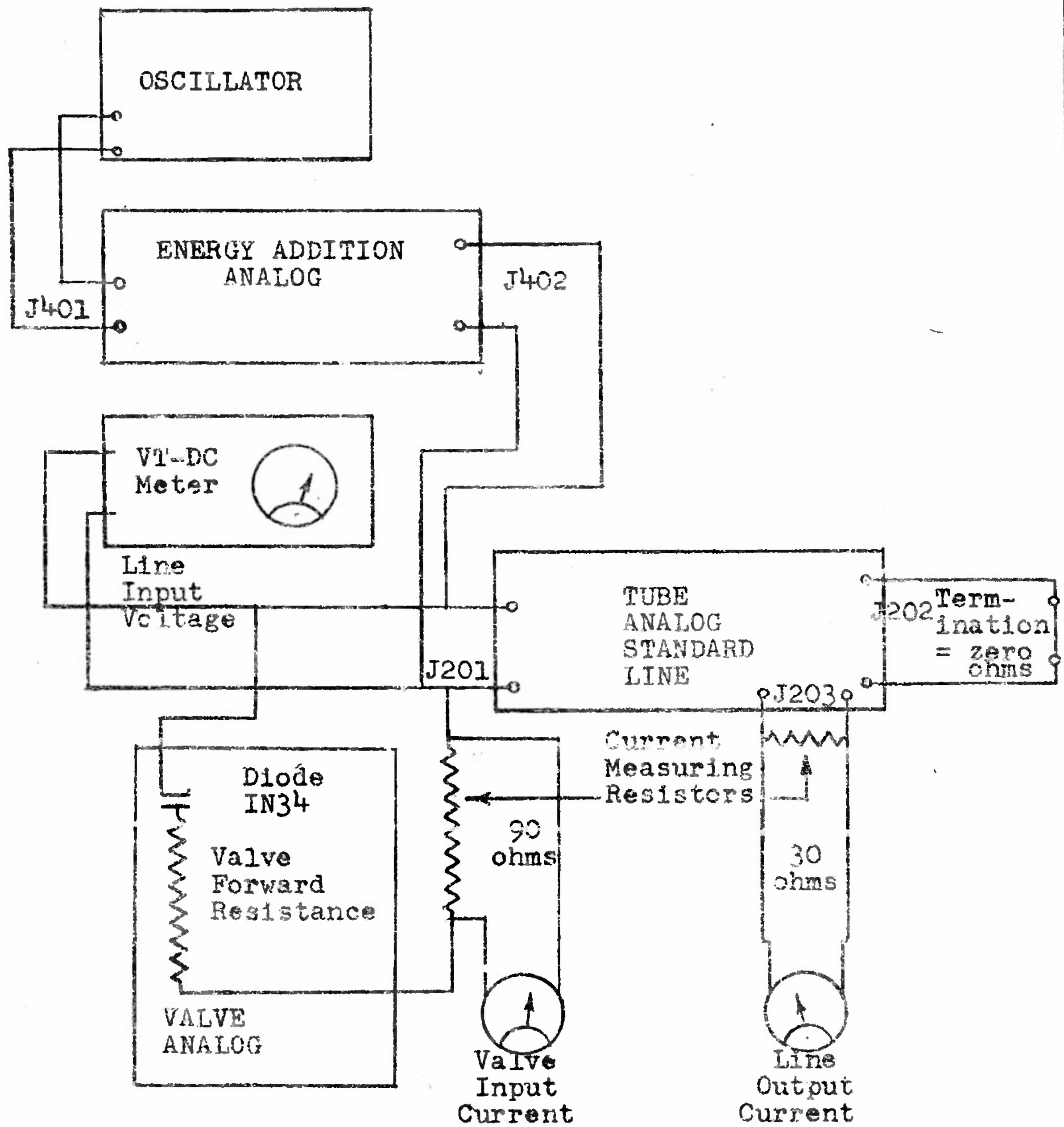

Fig. 3.2-1

[redacted]

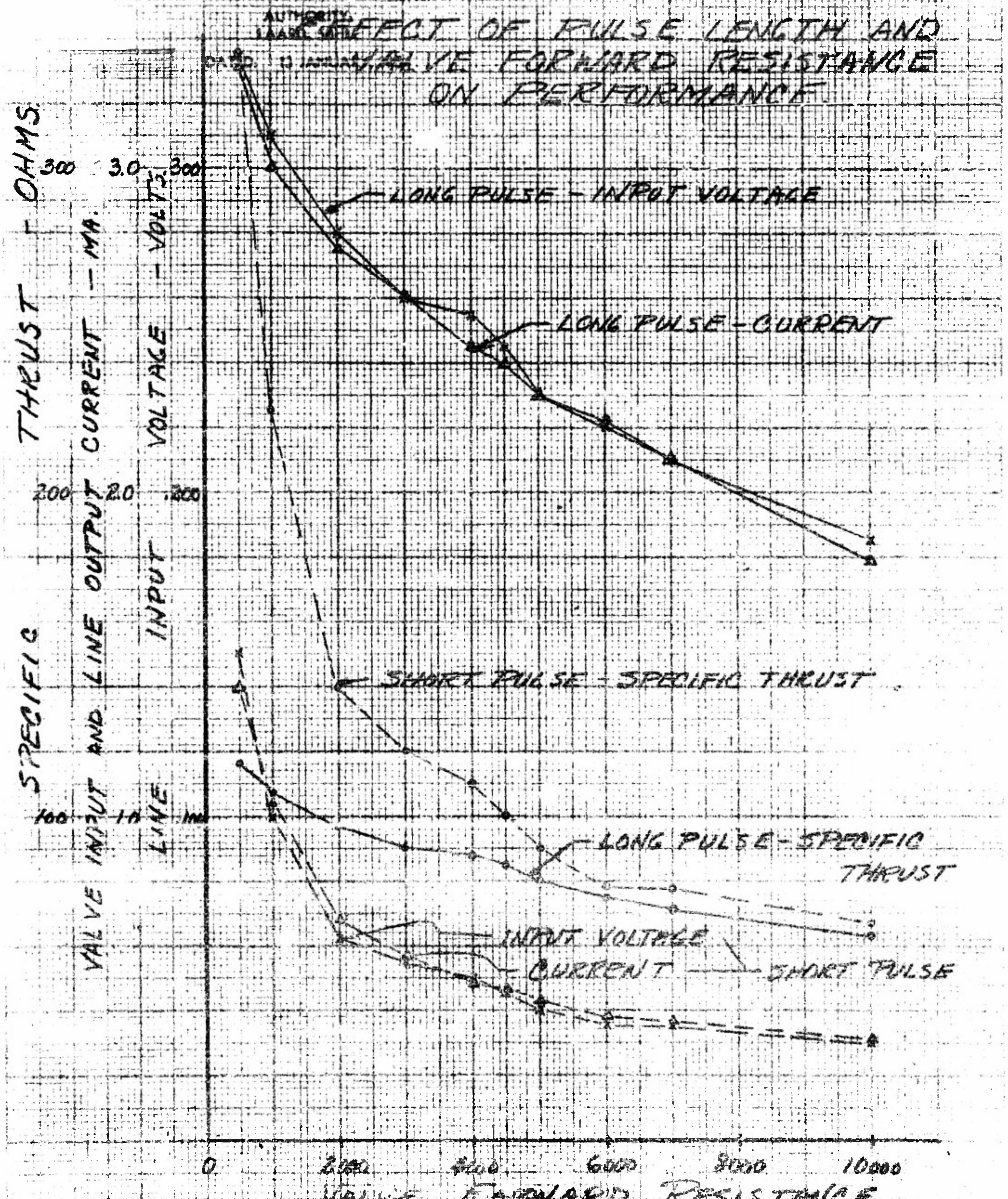

FIG. 3.2 - 2

TABLE 3.2 - 3.

Rec. No.	Pulse Length -sec.	Valve Res. ohms	Line Term. ohms	Total Source Current ma.	Valve Input Line Input Voltage	Valve Input Line Output Current ma.	Specific Thrust Ohms
1.	$.6 \times 10^{-3}$	500	30	2.89	.335	3.31	116
2.	"	1000	"	2.89	.31	3.00	107
3.	"	2000	"	2.89	.28	2.75	97
4.	"	3000	"	2.89	.26	2.61	90
5.	"	4000	"	2.89	.255	2.45	88
6.	"	4500	"	2.89	.245	2.40	85
7.	"	5000	"	2.89	.23	2.30	80
8.	"	6000	"	2.89	.22	2.22	75
9.	"	7000	"	2.89	.21	2.10	71
10.	"	10000	"	2.89	.185	1.79	63
11.	$.1 \times 10^{-3}$	500	30	.445	.15	1.40	336
12.	"	1000	"	.445	.10	1.04	225
13.	"	2000	"	.445	.062	.68	140
14.	"	3000	"	.445	.055	.57	120
15.	"	4000	"	.445	.050	.48	110
16.	"	4500	"	.445	.045	.46	100
17.	"	5000	"	.445	.040	.43	90
18.	"	6000	"	.445	.035	.38	78
19.	"	7000	"	.445	.035	.37	78
20.	"	10000	"	.445	.030	.31	67

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FIG. 3.2-4

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DATA OF SEPTEMBER 23, 1953

Driven System: Frequency = 1000 cps
Pulse Length = .6 x 10^{-3} sec   L = 1.0 hy   C = .032 uf
Standard Line Termination = zero ohms
Diode Valve - IN34 Valve forward resistance = 7000 ohms

SPECIFIC THRUST = 1.32

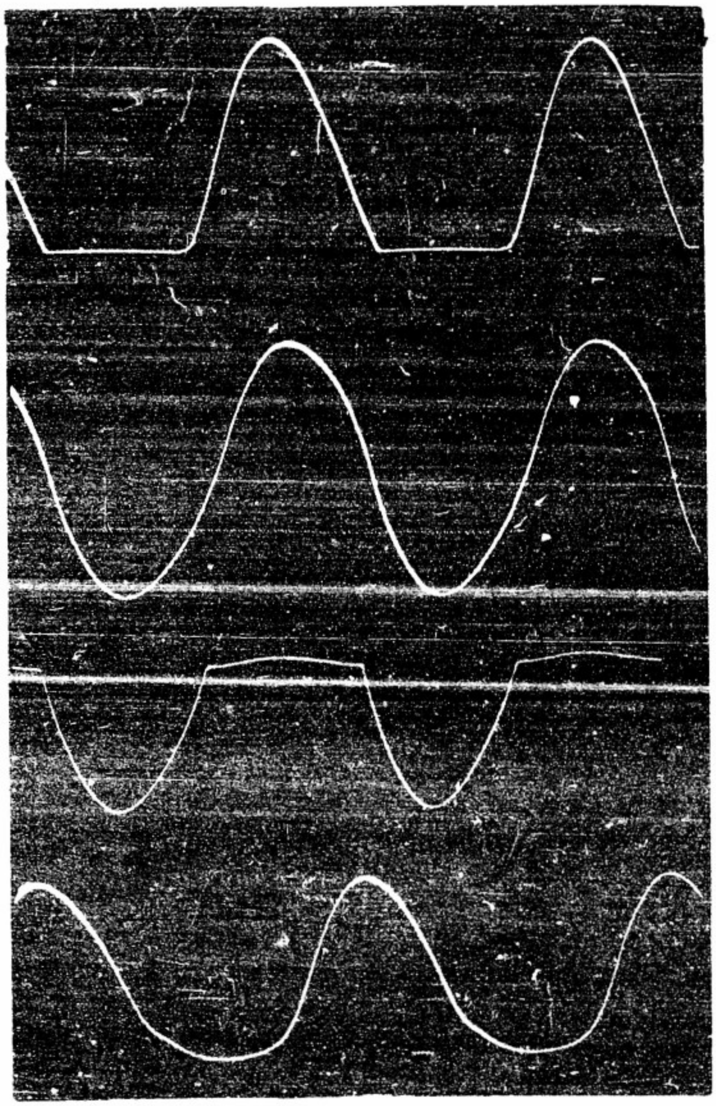

Photo No. 17

Source Current: Zero at 0
Average Current = 0
Total Current = 68 ua
across 100 ohms on X2
Scope Sensitivity = .1 v/div
.7 v peak

Photo No. 18

Line Input Voltage: Zero at 0
Average Voltage = .18 on X1
Scope Sensitivity = 10/v div.

Photo No. 19

Valve Input Current: Zero at 0
Average Current = 46 ua
across 90 ohms on X2
Scope Sensitivity = .1 v/div

Photo No. 20

Line Output Current: Zero at 0
Average Current = 30 ua
across 30 ohms on X1
Scope Sensitivity = .02 v/div.

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FIG. 3.2-5

DATA OF SEPTEMBER 23, 1953

Driven System: Frequency = 1000 cps
Pulse Length = $.6 \times 10^{-3}$ sec L = 1.0 hy C = .032 uf
Standard Line Termination = zero ohms
Diode Valve = IN34 Valve forward resistance = 4500 ohms

SPECIFIC THRUST = 1.57

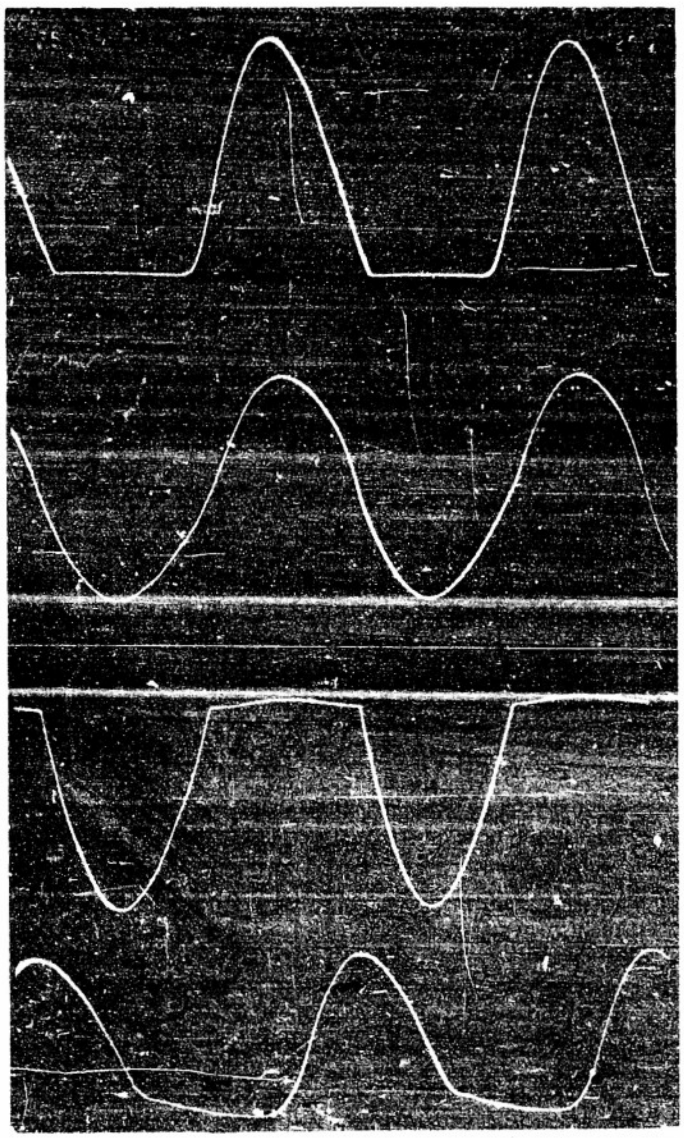

Photo No. 25

Source Current: Zero at 0
Average Current = 0
Total Current = 78 ua
across 100 ohms on X2
Scope Sensitivity = .1 v/div
.8 v peak

Photo No. 26

Line Input Voltage: Zero at 0
Average Voltage = .245 on X1
Scope Sensitivity = 10 v/div

Photo No. 27

Valve Input Current: Zero at 0
Average Current = 60.5 ua
across 90 ohms on X1
Scope Sensitivity = .1 v/div

Photo No. 28

Line Output Current: Zero at 0
Average Current = 39 ua
across 30 ohm on X1
Scope Sensitivity = .02 v/div

FIG. 3.2-6

DATA OF SEPTEMBER 23, 1953

Driven System: Frequency = 1000 cps
Pulse Length = .6 x 10^{-3} sec L = 1.0 hy C = .032 uf
Standard Line Termination = zero ohms
Diode Valve - IN34 Valve forward resistance = 500 ohms

SPECIFIC THRUST = 2.26

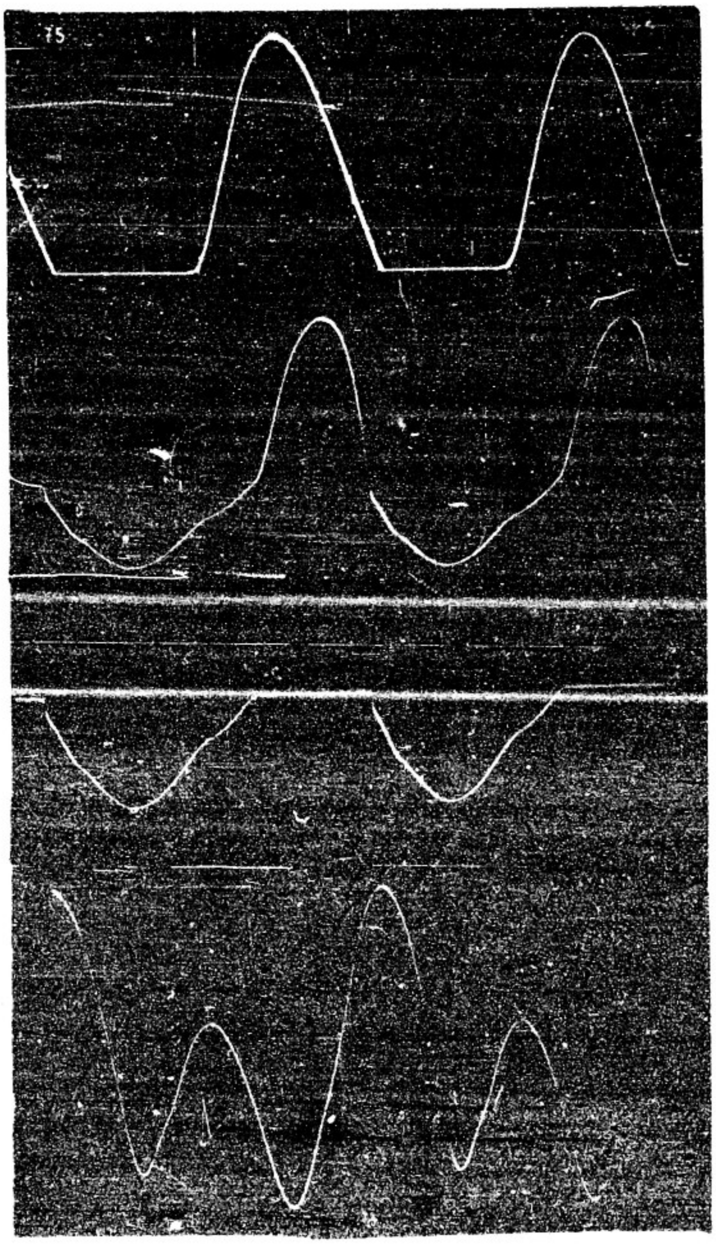

Photo No. 21

Source Current: Zero at 0
Average Current = 0
Total Current = 74 ua
across 100 ohms on X2
Scope Sensitivity = .1 v/div
.8 v peak

Photo No. 22

Line Input Voltage: Zero at 0
Average Voltage = .335 on X1
Scope Sensitivity = 2 v/div

Photo No. 23

Valve Input Current: Zero at 0
Average Current = 84 ua
across 90 ohms on X2
Scope Sensitivity = .2 v/div

Photo No. 24

Line Output Current: Zero at -5
Average Current = 53.5 ua
across 30 ohms on X1
Scope Sensitivity = .02 v/div

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DATA OF SEPTEMBER 23, 1953

Driven System: Frequency = 1000 cps
Pulse Length = $.1 \times 10^{-3}$ sec L = .1 hy C = .0022 uf
Standard Line Termination = zero ohms
Diode Valve - IN34 Valve forward resistance - 7000 ohms

SPECIFIC THRUST = 1.46

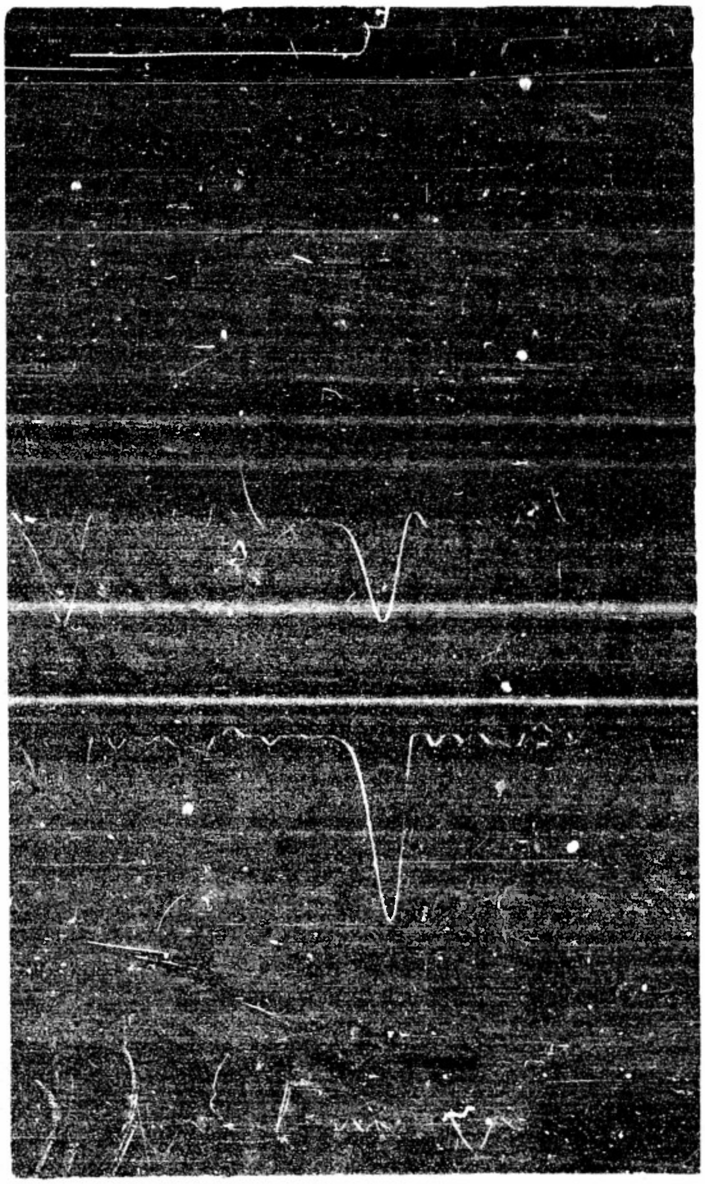


Photo No. 13

Source Current: Zero at -5
Average Current = 0
Total Current = 24 ua
across 100 ohms on X1
Scope Sensitivity = .1 v/div
.77 v peak

Photo No. 14

Line Input Voltage: Zero at 0
Average Voltage = .035 on X1
Scope Sensitivity = .5 v/div

Photo No. 15

Valve Input Current: Zero at 0
Average Current = 9.5 ua
across 90 ohms on X2
Scope Sensitivity = .05 v/div

Photo No. 16

Line Output Current: Zero at 0
Average Current = 6 ua
across 30 ohms on X1
Scope Sensitivity = .02 v/div

FIG. 3.2-8

DATA OF SEPTEMBER 23, 1953

Driven System: Frequency = 1000 cps
Pulse Length = $.1 \times 10^{-3}$ sec L = .1 hy C = .0022 uf
Standard Line Termination = zero ohms
Diode Valve - IN34 Valve forward resistance = 4500 ohms

SPECIFIC THRUST = 1.875

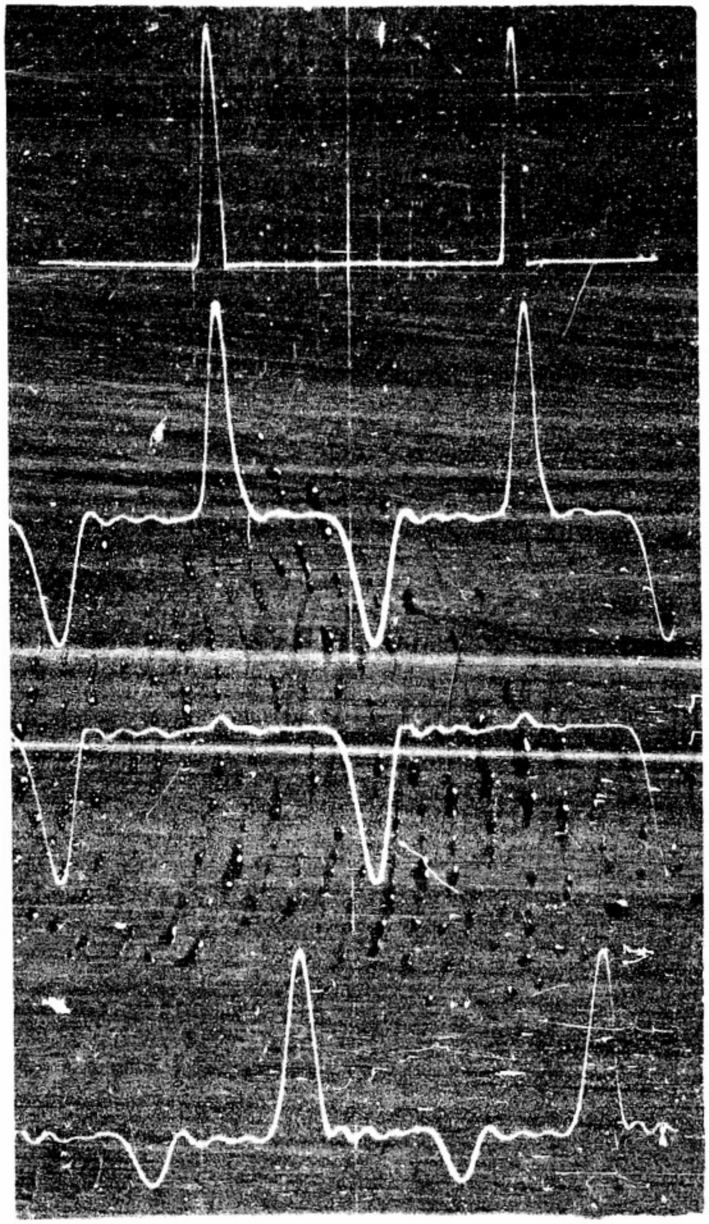


Photo No. 9

Source Current: Zero at -5
Average Current = 0
Total Current = 24 ua
across 100 ohms on X1
Scope Sensitivity = .1 v/div
.77 v peak

Photo No. 10

Line Input Voltage: Zero at 0
Average Voltage = .045 on X1
Scope Sensitivity = 5 v/div

Photo No. 11

Line Output Current: Zero at 0
Average Current = 11.5 ua
across 90 ohms on X2
Scope Sensitivity = .05 v/div

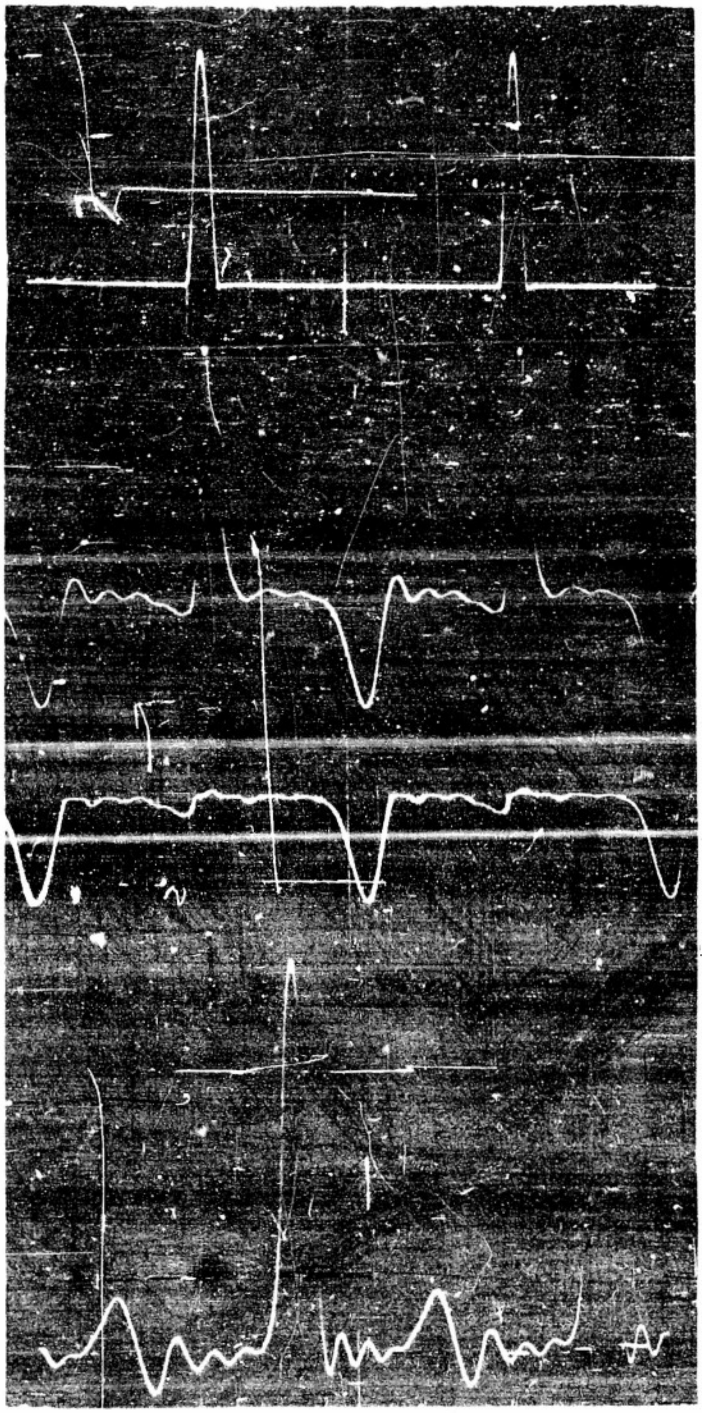
Photo No. 12

Line Output Current: zero at 0
Average Current = 7.5 ua
across 30 ohms on X1
Scope Sensitivity = .05 v/div

FIG. 3.2-9

DATA OF SEPTEMBER 23, 1953

Driven System: Frequency = 1000 cps
Pulse Length = $.1 \times 10^{-3}$ sec L = .1 hy C = .0022 uf
Standard Line Termination = zero ohms
Diode Valve - IN34 Valve forward resistance = 3000 ohms



SPECIFIC THRUST = 2.29

Photo No. 5

Source Current: Zero at -5
Average Current = 0
Total Current = 24 ua across 100 ohms on X1
Scope Sensitivity = .1 v/div
.77 v peak

Photo No. 6

Line Input Voltage: Zero at 0
Average Voltage = .055 on X1
Scope Sensitivity = 3.3 v/div

Photo No. 7

Valve Input Current: Zero at 0
Average Current = 14 ua
across 90 ohms on X2
Scope Sensitivity = .1 v/div

Photo No. 8

Line Output Current: Zero at -5
Average Current = 9.5 ua
across 30 ohms on X1
Scope Sensitivity = .02 v/div.

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FIG. 3.2-10

DATA OF SEPTEMBER 23, 1953

Driven System: Frequency = 1000 cps
Pulse Length = .1 x 10^{-3} sec L = .1 hy C = .0022 uf
Standard Line Termination = zero ohms
Diode Valve - IN34 Valve forward resistance = 500 ohms

SPECIFIC THRUST = 6.25

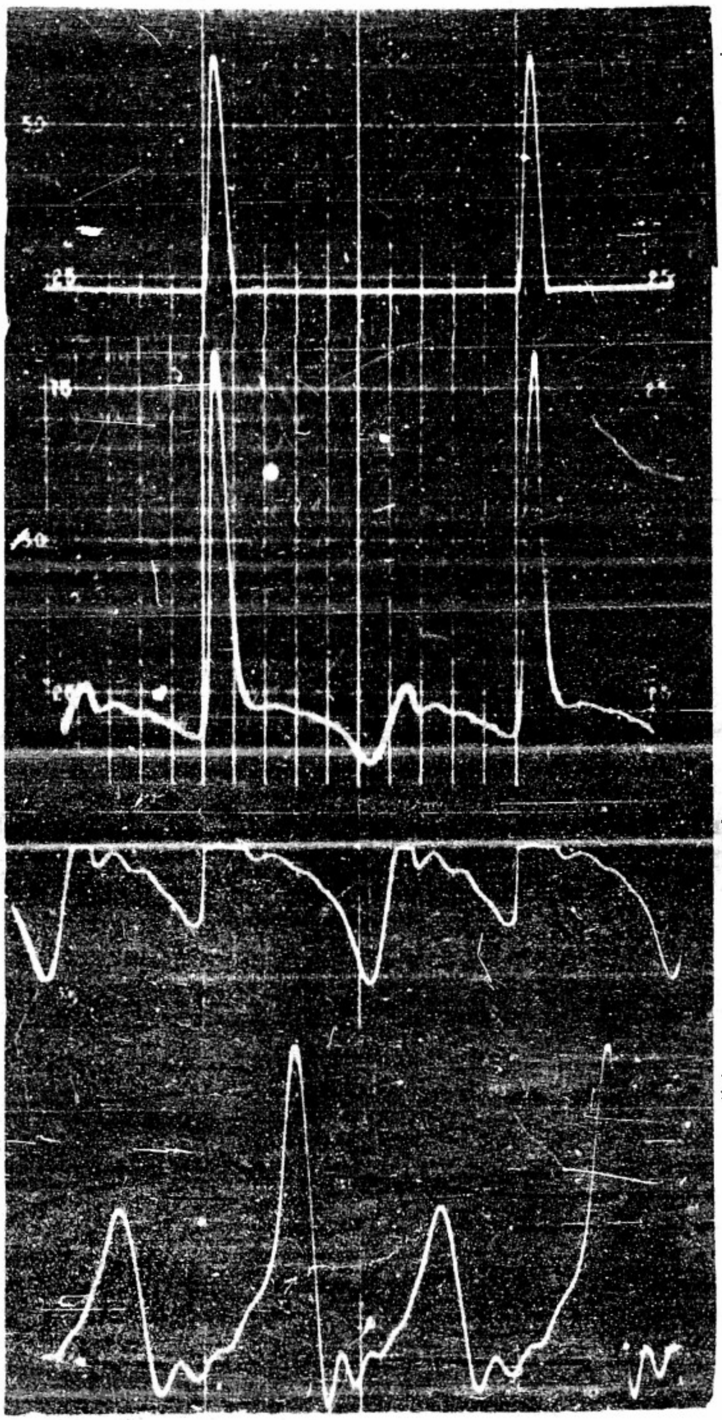

Photo No. 4

Source Current: Zero at -5
Average Current = 0
Total Current = 24 ua
across 100 ohms on X1
Scope Sensitivity = .1 v/div
.77 v peak

Photo No. 1

Line Input Voltage: Zero at -5
Average Voltage = 15 on X1
Scope Sensitivity = 2 v/div

Photo No. 2

Valve Input Current: Zero at 0
Average Current = 35.5 ua
across 90 ohms on X2
Scope Sensitivity = .1 v/div

Photo No. 3

Line Output Current: Zero at -5
Average Current = 22.5 ua
across 30 ohms on X1
Scope Sensitivity = .02 v/div

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FIG. 3.2-11

DATA OF SEPTEMBER 23, 1953

Driven System: Frequency = 260 cps
Pulse Length = .44 x 10^{-3} sec. L = 1.0 hy C = .022
Standard Line Termination = zero ohms
Diode Valve - IN34 Valve forward resistance = 650 ohms

SPECIFIC THRUST = 8.25

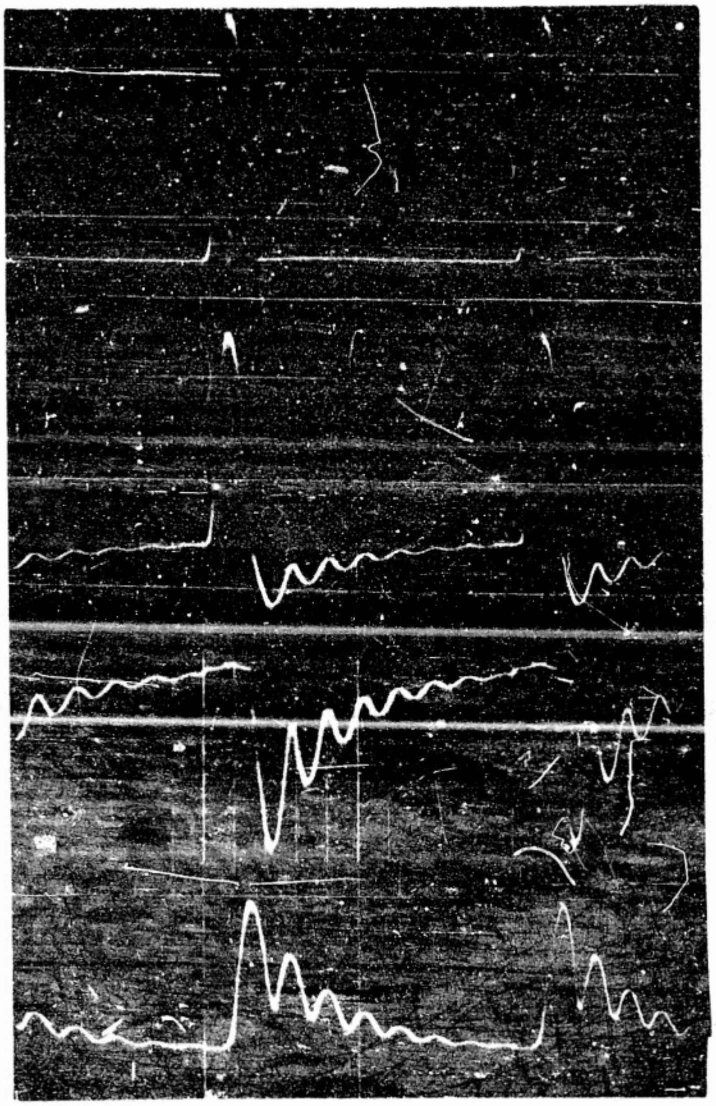

Photo No. 29

Source Current: Zero at 0
Average Current = 0
Total Current = 40 ua
across 100 ohms on X1
Scope Sensitivity = .1 v/div
.85 v peak

Photo No. 30

Line Input Voltage: Zero at 0
Average Voltage = .33 on X1
Scope Sensitivity = 5 v/div

Photo No. 31

Valve Input Current: Zero at 0
Average Current = 77 ua
across 90 ohms on X1
Scope Sensitivity = .2 v/div

Photo No. 32

Line Output Current: Zero at 0
Average Current = 50 ua
across 30 ohms at X1
Scope Sensitivity = .1 v/div